FORM PTO-1390 (REV 10-2000)

U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371

ATTORNEY'S DOCKET NUMBER	
3869-24	
U.S. APPLICATION NO. (If known, see 37 CFR 1.5)	
To Be Assigned 09/936854	

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/AU00/00411	05 May 2000	06 May 1999

TITLE OF INVENTION: CONTROL OF SUPPLIED PRESSURE IN ASSISTED VENTILATION

APPLICANT(S) FOR DO/EO/US: BERTHON-JONES, Michael et al.

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☒ This is an express request to promptly begin national examination procedures (35 U.S.C. 371(f)).
4. ☒ The US has been elected by the expiration of 19 months from the priority date (PCT Article 31).
5. ☒ A copy of the International Application as filed (35 U.S.C. 371(c)(2))
   a. ☒ is attached hereto (required only if not communicated by the International Bureau).
   b. ☐ has been communicated by the International Bureau.
   c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☐ An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)).
7. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))
   a. ☐ are attached hereto (required only if not communicated by the International Bureau).
   b. ☐ have been communicated by the International Bureau.
   c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
   d. ☒ have not been made and will not be made.
8. ☐ An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☐ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. ☐ An English language translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11 to 16 below concern document(s) or information included:

11. ☒ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. ☒ A FIRST preliminary amendment.
    ☐ A SECOND or SUBSEQUENT preliminary amendment.
14. ☐ A substitute specification.
15. ☐ A change of power of attorney and/or address letter.
16. ☒ Other items or information: Copy of the International Preliminary Examination Report; Copies of the References cited in the Information Disclosure Statement (3 items); Return Receipt Postcard

U.S. APPLICATION NO. (if known, see 37 CFR 1.5)	INTERNATIONAL APPLICATION NO.	ATTORNEY'S DOCKET NUMBER
To Be Assigned 09/936854	PCT/AU00/00411	3869-24

17. ☒ The following fees are submitted:

	CALCULATIONS PTO USE ONLY	
BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)) :		
Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO **$1000.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO **$860.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO **$710.00**		
International preliminary examination fee paid to USPTO (37 CFR 1.482) but all claims did not satisfy provisions of PCT Article 33(1)-(4) **$690.00**		
International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(1)-(4) **$100.00**		
ENTER APPROPRIATE BASIC FEE AMOUNT =	$ 1000.00	
Surcharge of **$130.00** for furnishing the oath or declaration later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492(e)).	$	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	44 - 20 =	24	X **$18.00**	$ 432.00	
Independent claims	6 - 3 =	3	X **$80.00**	$ 240.00	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ **$270.00**	$ 270.00	
TOTAL OF ABOVE CALCULATIONS =				$ 1,942.00	
☐ Applicant claims small entity status. See 37 CFR 1.27. The fees indicated above are reduced by 1/2.				$	
SUBTOTAL =				$	
Processing fee of **$130.00** for furnishing the English translation later than ☐20 ☐30 months from the earliest claimed priority date (37 CFR 1.492(f)). +				$	
TOTAL NATIONAL FEE =				$	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). **$40.00** per property +				$	
TOTAL FEES ENCLOSED =				$ 1,942.00	
				Amount to be refunded:	$
				charged:	$

a. ☒ A check in the amount of $ 1,942.00 to cover the above fees is enclosed.

b. ☐ Please charge my Deposit Account No. 07-1730 in the amount of $_____ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 07-1730. A duplicate copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

CHURCHILL, Raymond B., Jr.
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SIGNATURE:

CHURCHILL, Raymond B., Jr.
NAME

44,617
REGISTRATION NUMBER

Attorney's Docket No. 3869-24

IN THE UNITED STATES

[ ] RECEIVING OFFICE (RO/US)
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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/AU00/00411	05 May 2000 (05.05.00)	06 May 1999 (06.05.99)

TITLE OF THE INVENTION

CONTROL OF SUPPLIED PRESSURE IN ASSISTED VENTILATION

APPLICANT

Michael BERTHON-JONES et al.

Box PCT
Commissioner for Patents
Washington, D.C. 20231
ATTENTION: DO/EO/US

VERIFIED CERTIFICATION OF EXPRESS MAILING DATE (INTERNATIONAL APPLICATION (37 CFR 1.10(c))

I declare that on 17 September 2001 I deposited with the United States Postal Service in an envelope "Express Mail, Post Office to Addressee", bearing Label Number EL 803334150US, addressed to the "Box PCT, Commissioner for Patents, Washington, D.C. 20231" and having an express mail certification which I executed, the following papers:

Transmittal Letter to the United States Designated/Elected Office (DO/EO/US) concerning a filing under 35 U.S.C.371, duly executed; Copy of the published International Application; Copy of the International Preliminary Examination Report (3 pages); Information Disclosure Statement (2 pages), Form PTO-1449 (1 page) along with the copies of the references cited (3 items); Check for $ 1,942.00 (filing fees); Preliminary Amendment (3 pages) along with Appendix 1 (2 pages); and Return Receipt Postcard

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18, of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Zoya V. Chernina
(Typed or printed name of person making this verified statement)

Date: 17 September 2001

Zoya Chernina
(Signature of person making this verified statement)

(Verified Certification of Express Mailing Date (International Application))

Docket No. 3869-24

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant(s) :	Michael Berthon-Jones et al.	**Group Art Unit**: To Be Assigned	
Serial No. :	To Be Assigned	**Examiner**	: To Be Assigned
Filing Date :	Enclosed Herewith		
For :	CONTROL OF SUPPLIED PRESSURE IN ASSISTED VENTILATION		

Commissioner for Patents
Box PCT
Washington, D.C. 20231
Attention: DO/EO/US

PRELIMINARY AMENDMENT

Sir:

Prior to the substantive examination of the subject application please amend thereof as follows:

In the claims:

Please amend claims 8, 12-13, and 20-23 as follows. (A marked-up version of the claims is presented on page 1of the Appendix 1 attached hereto).

8 (Amended). A method as claimed in one of claims 4 - 7, wherein, for the case of said longterm average exceeding said threshold, said determining step includes a condition that said excess must occur for a minimum period of time before it is determined that a potential or actual overpressure is occurring.

12 (Amended). A method as claimed in one of claims 4 - 7, wherein said longterm average is of the order of minutes.

13 (Amended). A method as claimed in one of claims 4 - 7, wherein said longterm average is taken over ten or more breaths.

20 (Amended). Apparatus as claimed in one of claims 16 - 19, wherein, for the case of said longterm average exceeding said threshold, the controller operates subject to the condition that the time in excess must be greater than a minimum period of time before it is determined that a potential or actual overpressure is occurring.

21 (Amended). Apparatus as claimed in one of claims 16 - 19, further comprising alarm signalling means, coupled to said controller, for indicating that an alarm state exists if the threshold value is approached or exceeded.

22 (Amended). Apparatus as claimed in one of claims 16 - 19, wherein said controller determines the longterm average in the order of minutes.

23 (Amended). Apparatus as claimed in one of claims 16 - 19, wherein said controller determines the longterm average over ten or more breaths.

REMARKS

Claims 8, 12-13, and 20 through 23 have been amended to correct their dependency.

It is respectfully submitted that no new matter has been added by the aforementioned amendment. Early and favorable examination is earnestly requested.

Respectfully submitted
GOTTLIEB, RACKMAN & REISMAN, P.C.

Dated: 9/17/01

By: _____
Raymond B. Churchill, Jr.
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APPENDIX 1

MARKED-UP VERSION OF THE CLAIMS

8 (Amended). A method as claimed in [any] one of claims 4 [to] - 7, wherein, for the case of said longterm average exceeding said threshold, said determining step includes a condition that said excess must occur for a minimum period of time before it is determined that a potential or actual overpressure is occurring.

12 (Amended). A method as claimed in [any] one of claims 4 [to 11] - 7, wherein said longterm average is of the order of minutes.

13 (Amended). A method as claimed in [any] one of claims 4 [to 11] -7, wherein said longterm average is taken over ten or more breaths.

20 (Amended). Apparatus as claimed in [any] one of claims 16 [to] - 19, wherein, for the case of said longterm average exceeding said threshold, the controller operates subject to the condition that the time in excess must be greater than a minimum period of time before it is determined that a potential or actual overpressure is occurring.

21 (Amended). Apparatus as claimed in [any] one of claims 16 [to 20] -19, further comprising alarm signalling means, coupled to said controller, for indicating that an alarm state exists if the threshold value is approached or exceeded.

22 (Amended). Apparatus as claimed in [any] one of claims [14 to 21] 16-19, wherein said controller determines the longterm average in the order of minutes.

23 (Amended). Apparatus as claimed in [any] one of claims [14 to 21] 16-19, wherein said controller determines the longterm average over ten or more breaths.

CONTROL OF SUPPLIED PRESSURE IN ASSISTED VENTILATION

Field of the Invention

This invention relates to Non Invasive Positive Pressure Ventilation (NIPPV) treatment apparatus for the provision of assisted ventilation. Particularly, the invention concerns the control of treatment pressure supplied to a subject.

Background Art

NIPPV apparatus function to supply a patient with a supply of clean breathable gas (usually air, with or without supplemental oxygen) at a therapeutic pressure or pressures, at appropriate times during the subject's breathing cycle. The therapeutic pressure is also known as the ventilation pressure.

NIPPV apparatus typically include a flow generator, an air filter, a mask, an air delivery conduit connecting the flow generator to the mask, various sensors and a microprocessor-based controller. The flow generator may include a servo-controlled motor and an impeller. The flow generator may also include a valve capable of discharging air to atmosphere as a means for altering the pressure delivered to the patient as an alternative to motor speed control. The sensors measure, amongst other things, motor speed, gas volumetric flowrate and outlet pressure. The apparatus may optionally include a humidifier in the air delivery circuit. The controller may include data storage capacity with or without integrated data retrieval and display functions.

In this specification, NIPPV apparatus will be referred to as "assisted ventilation devices" which, in the broadest form, need not include all of the component features mentioned above.

Assisted ventilation devices are used for the treatment of many conditions, for example respiratory insufficiency or failure due to lung, neuromuscular or musculoskeletal disease and diseases of respiratory control.

Common to all forms of assisted ventilation is the need to control the pressure being applied to the patient. It is a known prior art technique to detect the peak pressure

and compare it against a maximum threshold value. If the threshold value is exceeded an alarm state occurs, and corrective action may be taken. This corrective action can be a short-term reduction in supplied pressure, followed by an increase back to the previous pressure.

Disclosure of the Invention

The present invention is directed to providing an alternative, advantageous approach to the problem of overpressure.

The invention discloses a method for controlling operation of an assisted ventilation device supplying pressurised gas to a patient, the method comprising the steps of:

determining a relatively longterm average of pressure of gas supplied to said patient; and

controlling the pressure supplied by said ventilation device with regard to said longterm average.

The invention further discloses a method for detecting the occurrence of a potential or actual overpressure during assisted ventilation, comprising the steps of determining a relatively longterm average of ventilation pressure, and determining whether the average approaches or exceeds a threshold value as being indicative of a potential or actual overpressure occurring.

The invention further discloses a method for controlling operation of an assisted ventilation device supplying pressurised gas to a patient, the method comprising the steps of:

measuring the currently delivered pressure;

determining a relatively longterm average of the measured pressure;

comparing said average against a threshold value; and

if the threshold value is approached or exceeded, controlling the pressure supplied by the device.

The invention yet further discloses assisted ventilation apparatus for detecting a potential or actual overpressure condition, comprising:

a blower to supply pressurised gas to a conduct, and in turn to a patient mask for connection with the entrance to a patient's airways:

a pressure sensor to detect the delivered pressure of gas in the conduit or at the mask, and provide a signal thereof; and

a controller receiving said pressure signal and having control over operation of the blower and operable to determine a relatively longterm average of the pressure signal and to control the supplied pressure with regard to said longterm average.

The invention yet further discloses assisted ventilation apparatus for detecting a potential or actual overpressure condition, comprising:

a blower to supply pressurised gas to a conduit, and in turn to a patient mask for connection with the entrance to a patient's airways;

a pressure sensor to detect the delivered pressure of gas in the conduit or at the mask, and provide a signal thereof; and

a controller, receiving the pressure signal and having control over operation of the blower, and operable to determine a relatively longterm average of the pressure signal, compare the average against a threshold value, and if the threshold value is approached or exceeded, to control the blower and thus the supplied pressure.

In one preferred form, an alarm state exists when said threshold is approached or exceeded, and on the occurrence of an alarm state, the assisted ventilation apparatus issues an alarm. Additionally or alternatively, the blower can be controlled to be switched-off or to be placed in a low pressure standby mode (for example 4 cmH_2O).

The invention further discloses a method for controlling operation of an assisted ventilation device supplying pressurised gas to a patient, the method comprising the steps of:

determining a relatively longterm average of supplied pressure; and

controlling said supplied pressure as a function of a waveform template, a target patient ventilation and said longterm average.

In relation to control of supplied pressure, the blower can be controlled to limit or reduce the supplied pressure. The reduction can be a non-linear function of time and/or pressure. Particularly, the degree of control can be stronger/greater as the threshold value is approached.

The longterm average can, in one form, be of the order of minutes. Alternatively, the average can be over ten or more breaths.

The threshold can be required to be exceeded for a minimum period of time before the alarm state is assessed as occurring.

The invention is advantageous in that it approaches the problem of overpressure from a relatively longer time scale than in the prior art. This is considered to be a more appropriate approach to the medical conditions that attend overpressure in assisted ventilation. For example, sustained overpressure causes a decrease in cardiac output, which would go largely untreated by the prior art arrangement discussed above.

Brief Description of the Drawings

Fig. 1 is a schematic block diagram of a representative assisted ventilation device, in the form of NIPPV apparatus;

Fig. 2 is a schematic block diagram of an overpressure detection circuit;

Fig. 3 shows traces of treatment pressure with time and the operation of an embodiment of the invention; and

Fig. 4 shows further traces of treatment pressure with time and the operation of an embodiment of the invention.

Description of Preferred Embodiments and Best Mode

An assisted ventilation device embodying one form of the invention is shown in Fig. 1, in which a blower comprising a motor 20 and an impeller 10, supplies breathable gas to a mask 11 for communication with a subject's airway via a delivery tube 12 and exhausting to atmosphere via an exhaust 13. Airflow at the mask 11 is measured using a pneumotachograph 14 and a differential pressure transducer 15. The mask flow signal from the transducer 15 is sampled by a microprocessor 16. Mask pressure is measured at a port 17 using a pressure transducer 18. The pressure signal from the transducer 15 is also sampled by the microprocessor 16. The microprocessor 16 sends an instantaneous mask pressure request signal to a servo 19, which compares

the pressure request signal with the actual pressure signal from the transducer 18 to control a motor 20 driving the impeller 10. The microprocessor's settings can be adjusted via a serial port 21.

It is to be understood that the mask could equally be replaced with a tracheotomy tube, endotracheal tube, nasal pillows, or other means of making a sealed connection between the air delivery means and the subject's airway.

In general terms, the invention is concerned with determining a relatively longterm average of ventilation pressure and avoiding occurrence of overpressure with regard thereto.

In one embodiment, the microprocessor 16 determines the long-term average of the actual treatment pressure, $\bar{p}$, and compares this against a threshold or maximum value, $\bar{P}_{max}$. If the threshold value is exceeded then corrective action may be taken.

The corrective action can be to issue an alarm, to switch-off the assisted ventilation device, to reduce the treatment pressure, or to control the blower in a more complex manner, an example of which is described in more detail below.

As shown in Fig. 2, the circuitry 30 receives a signal from the pressure transducer 15 indicative of the pressure in the air delivery conduit 12. The signal is amplified by an operational amplifier 32, then low-pass filtered 34 with a time constant of approximately one minute. Longer or shorter time constants would be appropriate depending on how long it was considered safe for the subject to be exposed to a relatively high mean pressure. In one embodiment, the time constant can be varied by way of an operator accessible control. The low-pass filtered signal passes to a comparator 36 where it is compared with a reference pressure signal corresponding to 15 cmH_2O, representing $\bar{P}_{max}$. The output from the comparator passes to both the servo 19 and a resettable monostable/one-shot 38. The resettable monostable/one-shot 38 is set to 30 seconds. Longer or short time periods would be suitable for specific assisted ventilation applications.

If the output from the comparator 36 is 'true', an indication that the low-pass filter signal exceeds $\bar{P}_{max}$, a "reduce" pressure signal is sent to the servo 19 (shown in

Fig. 1) on line 42. At this point, the resettable monostable/one-shot 38 starts to count down. If the count down reaches zero, then a stop signal is sent to the servo 19 on line 44. The count determines an adjustable tolerance on how long the alarm state has occurred before corrective action is taken. If the output from the comparator 36 is "false", there is no alarm state, and the resettable monostable/one-shot 38 is reset.

In another embodiment, implemented in software, the avoidance of overpressure is approached as the continuous monitoring of pressure as a function of the longterm average of the pressure. Referring once again to Fig. 1, the microprocessor 16 receives a signal representing mask pressure from the transducer 18. The microprocessor 16 controls the servo 19 such that the desired treatment pressure achieved satisfies the following equation:

$$P = P_0 + k.A.f(v,t) \qquad [1]$$

where:

P is the pressure setting for the blower (degree of support) (cmH_2O);

P_0 is a constant, the baseline pressure, chosen, for example, to keep the upper airway open, or to balance intrinsic PEEP (cmH_2O).

In one form,

$$k = 1. \qquad [2a]$$

In other forms,

$k = k'$, low pass filtered with time constant of 5 seconds [2b]

where:

$$k' = \begin{cases} 0, & \bar{p} \geq 15\ cmH_2O \\ 0.1, & \bar{p} = 14.9\ cmH_2O \\ 1, & \bar{p} \leq 14.5\ cmH_2O \end{cases} \qquad [3]$$

and linearly in between.

The purpose of making k nonlinear on $\bar{p}$ is to provide strong control as $\bar{P}_{max}$ is approached, with less effect further away from $\bar{P}_{max}$. The purpose of low pass filtering is to reduce distortion of the within-breath pressure-time profile.

The pressure modulation amplitude, A ($cm\ H_2O$) is given by:

$$A = g\int\left(\dot{V}_e - V_{TGT}\right)dt \qquad [4]$$

where g is a constant, $\dot{V}_e$ is the minute ventilation, and V_{TGT} is the target ventilation. A may be truncated to lie between A_{max} and A_{min}.

f is a function of at least one of time, t, and respiratory airflow, v, chosen to produce the desired pressure waveform. A range of functions is known to those skilled in the art. One example function corresponding to a spontaneous mode bi-level ventilator is:

$$f(v,t) = \begin{cases} 1, & v > 0 \\ 0 & otherwise \end{cases} \qquad [5a]$$

Another example function is:

$$f(v,t) = \begin{cases} 1, & t' < T_i \\ 0, & otherwise \end{cases} \qquad [5b]$$

where:

t' = t modulo T_{tot}

T_i = duration of inspiration

T_{tot} = duration of a breath

This corresponds to a "timed-mode" bilevel ventilator, with

$P = P_o$ during expiration; and

$P = P_o + A$ during inspiration

A number of simulations have been performed to demonstrate an embodiment of the invention in practise.

In Fig. 3, there is a sustained rise in peak pressure. In the top trace is shown the effect without the use of the present invention. The mean pressure exceeds a chosen $\overline{P}_{max}$ of 15 cmH_2O, which is undesirable. In the second trace, this is corrected by an embodiment of the invention, where the mean pressure is kept close to $\overline{P}_{max}$. The bottom trace shows the factor "k", and how it decreases from unity to approximately 0.5.

In Fig. 4, there is a transient rise in peak pressure. In the top trace, even without the practise of invention, the mean pressure closely approaches but does not exceed $\overline{P}_{max}$, which is permissible, even though the instantaneous pressure goes very high. With the invention practised, (second trace), the resultant pressure is little affected, because k remains close to unity (bottom trace)

In this embodiment, as the mean pressure threshold is approached, the degree of assistance is gradually reduced or limited. In another embodiment, both the baseline pressure, Po, and amplitude of ventilatory support, A, are progressively reduced as the mean pressure, $\overline{P}$, approaches the desired threshold pressure, $\overline{P}_{max}$.

The invention has been described with reference to a number of non-limiting examples, and it will be appreciated that the invention can be embodied in numerous other forms.

Claims:

1. A method for controlling operation of an assisted ventilation device supplying pressurised gas to a patient, the method comprising the steps of:

determining a relatively longterm average of pressure of gas supplied to said patient; and

controlling the pressure supplied by said ventilation device with regard to said longterm average.

2. A method for detecting the occurrence of a potential or actual overpressure during assisted ventilation, comprising the steps of:

determining a relatively longterm average of ventilation pressure; and

determining whether the average approaches or exceeds a threshold value as being indicative of a potential or actual overpressure occurring.

3. A method as claimed in claim 2, comprising the further step of issuing an alarm upon the determination of a potential or actual overpressure occurring.

4. A method for controlling operation of an assisted ventilation device supplying pressurised gas to a patient, the method comprising the steps of:

measuring the currently delivered pressure;

determining a relatively longterm average of the measured pressure;

comparing said average against a threshold value; and

if the threshold value is approached or exceeded, controlling the pressure supplied by the device.

5. A method as claimed in claim 4, wherein said controlling step includes limiting or reducing supplied gas pressure to the patient.

6. A method as claimed in claim 5, wherein, for the case of reducing supplied gas pressure, the reducing step is a non-linear function of time and/or pressure.

7. A method as claimed in claim 6, wherein the degree of reduction is greater as said threshold value is approached.

8. A method as claimed in any one of claims 4 to 7, wherein, for the case of said longterm average exceeding said threshold, said determining step includes a condition that said excess must occur for a minimum period of time before it is determined that a potential or actual overpressure is occurring.

9. A method for controlling operation of an assisted ventilation device supplying pressurised gas to a patient, the method comprising the steps of:

determining a relatively longterm average of supplied pressure; and

controlling said supplied pressure as a function of a waveform template, a target patient ventilation and said longterm average.

10. A method as claimed in claim 9, wherein said function is given by:

$$P = P_0 + k.A.f(v,t)$$

where:

P is said supplied pressure,

P_0 is a constant pressure,

K is a function of said longterm average,

A is a function of said target patient ventilation, and

$f(v,f)$ represents said waveform template.

11. A method as claimed in claim 9, wherein, in said controlling step, when said longterm average approaches a threshold value, strong control of said supplied pressure is provided.

12. A method as claimed in any one of claims 4 to 11, wherein said longterm average is of the order of minutes.

13. A method as claimed in any one of claim 4 to 11, wherein said longterm average is taken over ten or more breaths.

14. Assisted ventilation apparatus for detecting a potential or actual overpressure condition, comprising:

a blower to supply pressurised gas to a conduct, and in turn to a patient mask for connection with the entrance to a patient's airways:

a pressure sensor to detect the delivered pressure of gas in the conduit or at the mask, and provide a signal thereof; and

a controller receiving said pressure signal and having control over operation of the blower and operable to determine a relatively longterm average of the pressure signal and to control the supplied pressure with regard to said longterm average.

15. Assisted ventilation apparatus as claimed in claim 14, wherein said controller controls the supplied pressure as a function of a waveform template, a target patient ventilation and said longterm average.

16. Assisted ventilation apparatus for detecting a potential or actual overpressure condition, comprising:

a blower to supply pressurised gas to a conduit, and in turn to a patient mask for connection with the entrance to a patient's airways;

a pressure sensor to detect the delivered pressure of gas in the conduit or at the mask, and provide a signal thereof; and

a controller, receiving the pressure signal and having control over operation of the blower, and operable to determine a relatively longterm average of the pressure signal, compare the average against a threshold value, and if the threshold value is approached or exceeded, to control the blower and thus the supplied pressure.

17. Apparatus as claimed in claim 16, wherein said controller controls the supplied pressure by limitation or reduction.

18. Apparatus as claimed in claim 17, wherein, for the case of reducing supplied pressure, the controller reduces the pressure as a non-linear function of time and/or pressure.

19. Apparatus as claimed in claim 18, wherein the degree of reduction by the controller is greater as said threshold value is approached.

20. Apparatus as claimed in any one of claims 16 to 19, wherein, for the case of said longterm average exceeding said threshold, the controller operates subject

to the condition that the time in excess must be greater than a minimum period of time before it is determined that a potential or actual overpressure is occurring.

21. Apparatus as claimed in any one of claims 16 to 20, further comprising alarm signalling means, coupled to said controller, for indicating that an alarm state exists if the threshold value is approached or exceeded.

22. Apparatus as claimed in any one of claims 14 to 21, wherein said controller determines the longterm average in the order of minutes.

23. Apparatus as claimed in any one of claims 14 to 21, wherein said controller determines the longterm average over ten or more breaths.

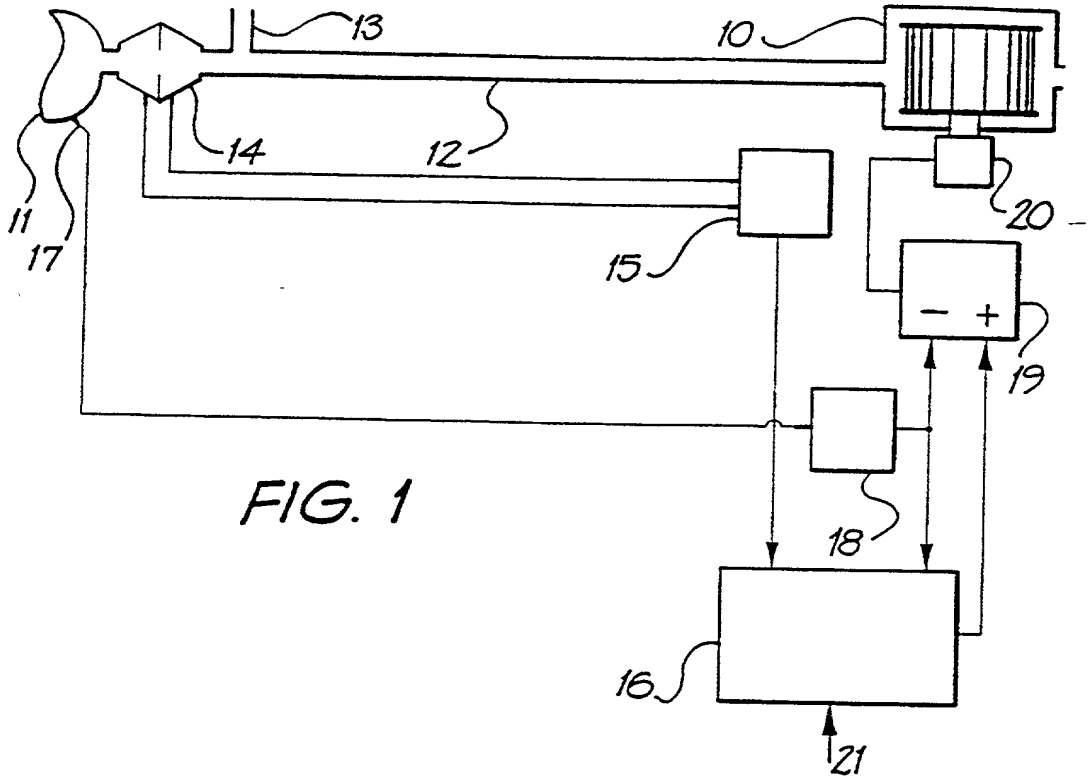

FIG. 1

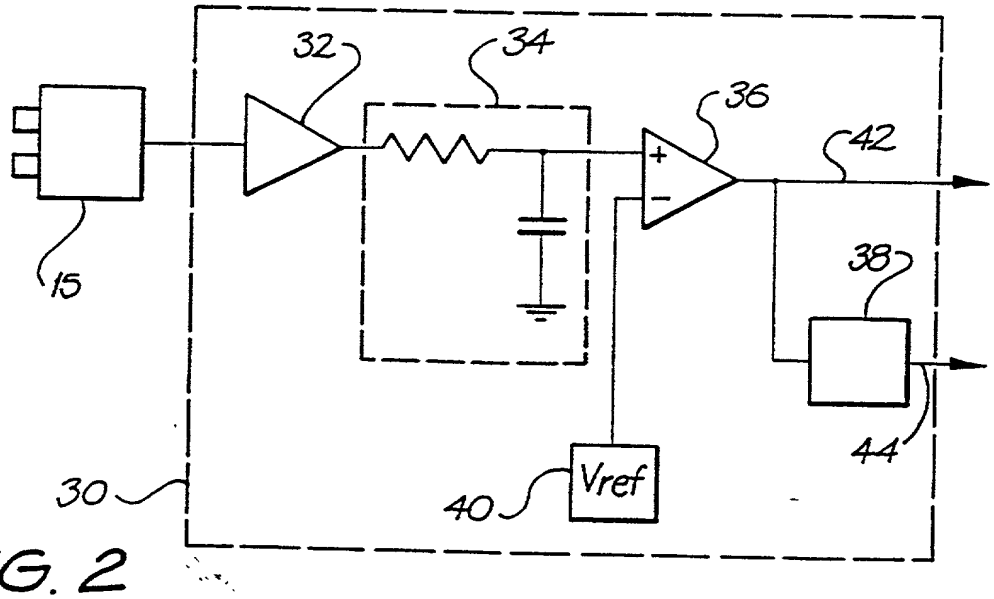

FIG. 2

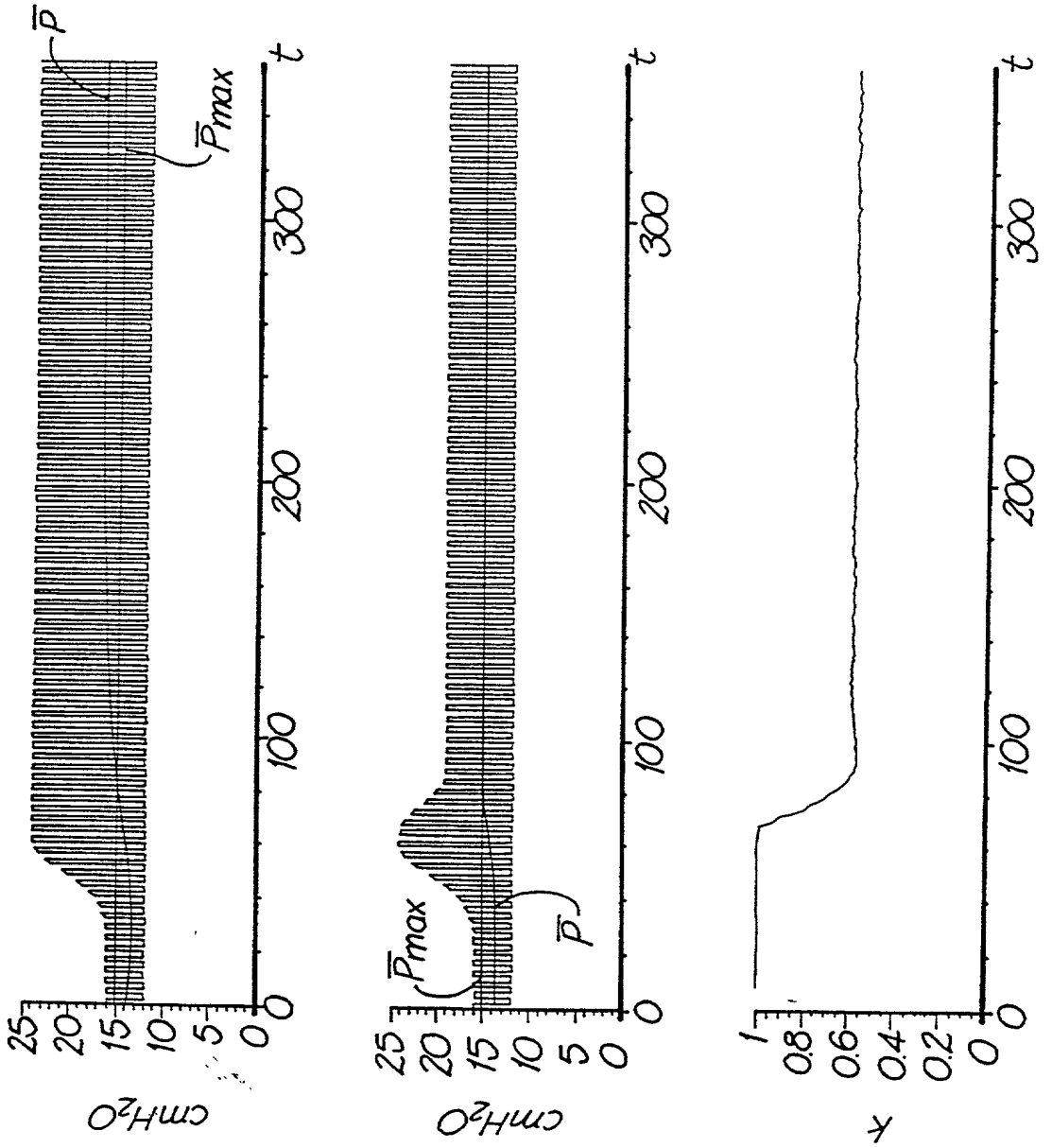

FIG. 3

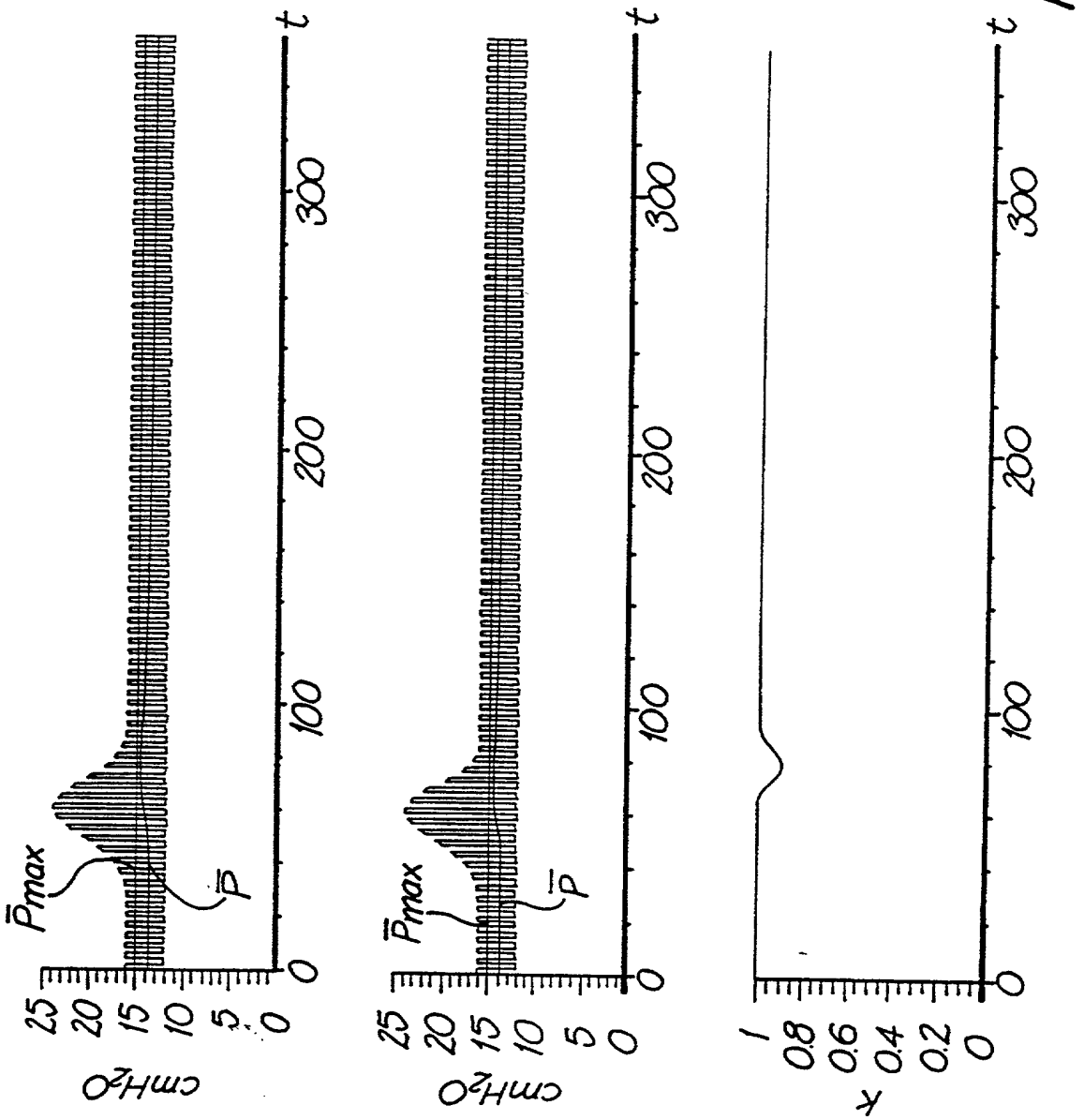
t
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FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU00/00411

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. [7]: A61M 16/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC: A61M 16/-

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DWPI: A61M 16/- & keywords

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 97/14462 A1 (UNIVERSITY OF FLORIDA) 24 April 1997	
A	EP 425092 A1 (RESPIRONICS INC.) 2 May 1991	
P, A	US 5901704 A (ESTES et. al.) 11 May 1999	

☐ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
1 June 2000	21 JUN 2000
Name and mailing address of the ISA/AU	Authorized officer
AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	VINCE BAGUSAUSKAS Telephone No : (02) 6283 2110

Form PCT/ISA/210 (second sheet) (July 1998)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/AU00/00411

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report	Patent Family Member		
WO 9714462	AU 73686/96		
EP 425092	AU 38508/93	CA 2024477	JP 7016517
US 5901704	AU 29268/92	EP 610405	WO 9308857

END OF ANNEX

LUNG CLASSIFICATION SCHEME, A METHOD OF LUNG CLASS IDENTIFICATION AND INSPIRATORY WAVEFORM SHAPES

Field of the Invention

This invention relates to systems for the artificial ventilation of patients, and, more particularly, to a classification scheme for different types of patients' lungs, a method of identifying lung classes, and, a method and apparatus for the delivery of ventilatory parameters including waveform, inspiratory time, inspiratory pause and tidal volume, among others, dependent upon the identified lung class.

Background of the Invention

The lungs can be characterized as a mass exchanger in which oxygen, anesthetics and/or medication are delivered through the alveoli to blood pumped from the heart, and carbon dioxide, and anesthetics during emergence, are removed from the blood for exhalation. The mass transfer rate and efficiency in either direction, i.e. removal or inflow of gaseous materials at the blood/gas interface, is dependent at least in part on the

distribution of ventilation to each lung. In turn, mechanical factors such as compliance and flow resistance within the bronchi and the different regions of the lungs affect the distribution of pulmonary ventilation. The term "compliance" refers to the elasticity of the lungs, or their ability to expand and contract during an inspiration and exhalation cycle, and is the inverse or mathematical reciprocal of stiffness. The flow resistance along the respiratory pathways refers to blockages or restrictions to the passage or flow of gaseous materials to and from the lungs.

Diseased or injured lungs may have markedly different compliances or flow resistances compared to healthy lungs. For example, one bronchus may have a higher flow resistance due to swelling of its mucus membrane that constricts its flow area compared to the bronchus associated with the other, unaffected lung. Additionally, one lung could be less compliant than the other due to trauma or aspiration of gastric acid from the stomach. A lung with lower resistance and/or lower compliance builds up pressure at a faster rate than the other lung when both are exposed to a common pressure or flowrate input at the trachea, or at the carina where the bronchi meet the trachea. Consequently, the distribution of ventilation in the lungs can become unequal such that the volume of gas in the right lung at the end of inspiration may not be equal to the volume of gas in the left lung. If both an abnormal lung and a healthy lung receive similar blood perfusion rates (Q), i.e. the same volume of blood

from the heart per unit time (cardiac output), but different ventilation or gas volume rates (V), there is an undesirable ventilation/perfusion ratio (V/Q) mismatch. This mismatch degrades the mass transfer or gas exchange rate, and the efficiency of such exchange, within the lungs. In turn, less carbon dioxide (and less gaseous and volatile anesthetics during emergence) come out of solution from the blood, while less oxygen (and less gaseous and volatile anesthetics during induction and maintenance) dissolve into the blood per unit time. Although the body's compensatory mechanisms will shunt the perfusion to favor the better ventilated lung, there is a limit to that self-regulatory action, particularly when it is depressed by some anesthetics.

Another physiological parameter which is of concern during ventilation and/or anesthesia of a patient is the mean pressure within the lungs over time (mean lung pressure, MLP). Higher mean lung pressures during mechanical ventilation can reduce the cardiac output or volume of blood pumped by the heart per unit time by interfering with the filling and emptying of the heart. Because the lungs and heart both reside in the chest cavity, excess pressure. and hence excess expansion of the lungs, can reduce cardiac output.

In view of these problems with ventilation of diseased or injured lungs, one design objective of ventilation apparatus and anesthesia systems is to equalize the distribution of ventilation in lungs of unequal

compliances and/or unequal resistances, while minimizing the mean lung pressure within the lungs. We numerically express distribution of ventilation as the "ventilation distribution ratio," or quotient of the volume of gas within the right lung over the volume in the left lung at the end of inspiration. Assuming the right and left lung to be of equal volume, the ventilation distribution ratio (R_v) should ideally be unity, or, for diseased or damaged lungs, as close to unity as possible.

A number of studies have been undertaken to determine the effectiveness of inspiratory waveform shaping as a means of optimizing the ventilation distribution ratio of lungs having unequal compliance and/or resistance, while minimizing mean lung pressure. The term "inspiratory waveform shaping" refers to the configuration of a pressure or flowrate waveform over time which is delivered by a ventilator (ICU (intensive care unit) or anesthesia) to the patient during mechanical inspiration. Currently, there are four flowrate waveforms commonly employed in ICU ventilators, including constant flowrate, linearly increasing flowrate, linearly decreasing flowrate and half-sine (0 to π) flowrate. Most anesthesia ventilators offer only a constant flowrate waveform. These flowrate waveforms have been utilized in various studies to assess the effect of using one waveform or another on the ventilation distribution ratio for different lung configurations, e.g. lungs having equal compliance and

unequal resistance (ECUR), and lungs with unequal compliance and equal resistance (UCER).

The results obtained from prior studies involving inspiratory waveform shaping have up to now contradicted one another. Furthermore, none of the studies have addressed the need for a lung classification scheme or how to identify/classify a patient's lung configuration. No suggestion is made as to how one might determine the particular characteristics of the lung of a given patient so that an appropriate inspiratory waveform or other ventilatory parameters might be selected and utilized. Further, the emphasis in prior studies has been to attempt to determine the "best" single pressure or flowrate inspiratory waveform for all types of lung conditions, even though the characteristics and behavior of lungs afflicted with emphysema, asthma and acute respiratory distress syndrome, for example, are very different.

Summary of the Invention

It is therefore among the objectives of this invention to provide a methodology for operating a ventilation apparatus and/or anesthesia system for use with patients having a variety of lung conditions, which attempts to equalize the distribution of ventilation in lungs with unequal resistance and/or unequal compliance, and, which minimizes the mean lung pressure over time.

These objectives are accomplished in a methodology which includes determining the class of the lungs of a given patient, selecting a pressure or flowrate waveform and other ventilatory parameters such as inspiratory pause and inspiratory time which are appropriate for that lung class, and then ventilating the patient with the selected inspiratory waveform and ventilatory parameters. New ventilation inspiratory waveforms are provided which have been found to be advantageous for certain types of lung classes. An inspiratory pause is generated by imposing a zero flowrate condition in the trachea or endotracheal tube (ETT).

One aspect of this invention is predicated upon the concept of determining the particular class of the lungs of a particular patient. There are a total of 16 possible variations of lung types, given that each lung of a patient has a certain left and right compliance and a certain left and right resistance. It has been determined through computer modeling and mathematical derivation, that these 16 lung types can be categorized into three general lung classes, including: (1) Class I: lungs having equal individual time constants, where the time constant of each lung is the product of its resistance and compliance; (2) Class II: lungs of unequal compliance, with no restriction on resistance; and, (3) Class III: lungs of equal compliance but unequal resistance. The lung classification scheme of this invention depends on the ability to identify for each patient which

of the three general lung classes mentioned above is applicable so that an appropriate inspiratory waveform and other ventilatory parameters such as inspiratory time and pause can be selected.

Clinical determination of the different lung classes is accomplished in the method of this invention using one or more algorithms generated by modified control software of commercially available computer-controlled ventilators.

One algorithm employs a constant (or any other) flowrate waveform wherein the time of inspiration is varied from a shorter time period to a longer time period, e.g. two seconds to four seconds, while maintaining all other ventilatory parameters constant. A measurement is taken of the end-tidal carbon dioxide concentration following exhalation after the shorter, two second inspiratory time, and then a second measurement of end-tidal carbon dioxide is taken upon exhalation after at least ten breaths or one minute at the longer, four second inspiratory time. In Class III lungs, it is believed that a substantial decrease in end-tidal carbon dioxide concentration will occur following ventilation for at least ten breaths or one minute with an increased inspiratory time. This is because it is believed that a better ventilation distribution ratio is obtained using a constant flowrate waveform with Class III lungs wherein the inspiratory time is increased. In turn, a better ventilation distribution ratio leads to better washout, which then leads to lower end tidal carbon dioxide

concentration. Class I and II lungs, on the other hand, are believed to show no decrease, or an increase, in end-tidal carbon dioxide concentration following exhalation under the same inspiratory time and tidal volume parameters. As a result, a Class III lung may be identified and distinguished from Class I and II lungs using this algorithm.

A second algorithm to detect Class III lungs involves the use of a newly implemented inspiratory waveform, a rising exponential flowrate inspiratory waveform, with an inspiratory pause (e.g., 25% of inspiratory time). It has been determined mathematically and by computer simulation that the ventilation distribution ratio for Class III lungs is substantially improved using a rising exponential flowrate inspiratory waveform where an inspiratory pause is employed, compared to the same waveform when there is no inspiratory pause. It is believed that a decrease in end-tidal carbon dioxide will occur following ventilation for at least ten breaths or one minute with the inspiratory pause compared to ventilation with the preceding waveform without the inspiratory pause. No lowering of end-tidal carbon dioxide is expected in a Class I lung under similar ventilatory parameters, and there is either an increase or no change in end-tidal carbon dioxide for Class II lungs under the same circumstances.

A third algorithm can be employed to identify Class III lungs which involves the use of a constant pressure waveform followed immediately by ventilation for at least ten breaths or one minute with a

rising exponential flowrate waveform, wherein both waveforms have the same tidal volume and inspiratory time. When using these consecutive waveforms on a patient with Class III lungs, it is believed that an increase of end-tidal carbon dioxide would follow inflation with the rising exponential flowrate waveform. No such change is expected for either Class I or Class II lungs, and therefore a Class III lung may be positively identified with this algorithm.

In addition to identifying the class of lungs by measuring the end-tidal carbon dioxide concentration, the method and apparatus of this invention contemplates lung class identification by the measurement of the intratracheal pressure trace. The intratracheal pressure trace is obtained by sampling the pressure at the distal tip of the endotracheal tube using a pressure sensor pneumatically connected to a pressure coupling port or lumen located at the distal tip of the endotracheal tube with which the patient is intubated. An inspiratory pause is added during mechanical ventilation to assist in identifying the lung class. In the presently preferred embodiment, the intratracheal pressure trace is divided into segments corresponding to different phases of inspiration, i.e., active inflation, inspiratory pause, beginning of expiration, and, end of expiration using the flow and pressure trace signals. Different algorithms, described in detail below, are then applied to the intratracheal pressure trace segments.

It has been observed that it is possible to differentiate between a Class I lung, and Class II or III lungs, by the intratracheal pressure trace during inspiration. A Class I lung exhibits a linear intratracheal pressure trace whereas Class II or Class III lungs have a non-linear pressure trace during active inflation, using a constant flowrate waveform. Such characteristics have been observed both with mechanical models and computer simulations of two compartment lungs. Importantly, it has been observed that Class III lungs can be readily identified by examining the intratracheal pressure trace during the inspiratory pause. By definition, there is no flow within an endotracheal tube during a true inspiratory pause. The volumes in the lung compartments can then redistribute according to the pressure differentials during the inspiratory pause. It has been observed that for Class III lungs, the pressure trace during inspiratory pause has a slowly decaying slope, whereas the pressure traces for Class I or II lungs quickly drop in a step fashion from a peak inspiratory pressure to a plateau. A Class III lung can thus be clearly distinguished from Class I and II lungs in this manner.

An examination of the intratracheal pressure trace during expiration is also helpful in identifying and differentiating between the different lung classes. It has been observed that for a Class II lung, the intratracheal pressure trace during exhalation follows two different time constants. The shorter time constant predominates at the start of exhalation

and quickly dies out, while the longer time constant persists and dominates toward the end of exhalation. Software within the apparatus of this invention takes the natural logarithm of the intratracheal pressure trace at the beginning and ending segments of exhalation, and samples the resulting slopes of the natural logarithms over time. It has been determined that if the slopes are markedly different, then the lung class is not a Class I lung, but could be a Class II or III lung. Using the inspiratory pause intratracheal pressure trace described above, a Class III lung can be positively identified as compared to a Class I or II lung. Consequently, Class I, II and III lung types can be differentiated from one another using a combination of the intratracheal pressure traces during expiration and during inspiratory pause.

Still another method of assisting in determining the lung characteristics of a particular patient involves quantification of the effective time constant of the entire respiratory system. In the presently preferred embodiment, a constant pressure waveform (pressure step input of time duration T_i) is applied at the carina and an analysis is undertaken of the resulting flow rate trace at the distal tip of the endotracheal tube. To obtain a constant pressure waveform at the carina, the pressure is sampled at the distal tip and a feedback loop within the apparatus herein is implemented to maintain the pressure thereat to the desired constant value. The flowrate at the distal tip of the endotracheal tube over time ($Q_{et}(t)$)

decays exponentially in response to a pressure step at the carina, with the maximum inspiratory flowrate, Q_{max}, corresponding to the initial flowrate, Q_{ett} (t=0). The point in time at which $Q_{ett}(t)$ equals exp (-1) • Q_{max} (0.368 Q_{max}) corresponds to the time constant of the entire respiratory system, and can be determined by measuring the flow at the endotracheal tube with the flow meter placed thereat.

Alternatively, the effective time constant of the entire respiratory system can also be quantified by an increasing ramp pressure input at the carina. For an increasing pressure waveform, $Q_{max} = Q_{ett}(T_i)$. The point in time when $Q_{ett}(t)$ reaches (1 - exp (-1)) (Q_{max}) = (1 - 0.368) Q_{max} = 0.632 Q_{max} is the time constant of the entire respiratory system and can be determined in the same way as with the constant pressure technique.

Once the class of the lungs of a given patient has been determined by employing one or more of the algorithms discussed above, an appropriate inspiratory waveform and other ventilatory parameters can be selected which are best suited for that lung classification. Another aspect of this invention is predicated upon the concept that different types of inspiratory waveforms and ventilatory parameters are more appropriate for different classes of lungs than others, and, in fact, some types of inspiratory waveforms can be harmful when used with patients having certain lung conditions. Keeping in mind that the goal is to obtain a ventilation distribution ratio which approaches unity with lungs of different

time constants, while minimizing the mean lung pressure, it has been found that the rising exponential inspiratory waveform is preferred in most instances except for Class III lungs. A constant pressure inspiratory waveform, for example, while it causes the ventilation distribution ratio to approach 1.0 for a Class III lung, may not be indicated for certain patients with Class III lungs because it has been found to increase mean lung pressure in such patients. Further, longer inspiratory times and the use of an inspiratory pause provide a more even ventilation distribution ratio in Class III lungs. With respect to Class I and Class II lungs, inspiratory waveforms whose time derivatives are strong functions of time are recommended to obtain more even ventilation distribution ratios and reduced mean lung pressures. The use of an inspiratory pause is not recommended for either Class I or Class II lungs because it increases mean lung pressure and/or produces a more uneven ventilation distribution ratio.

The appropriately selected ventilation inspiratory waveform and other ventilatory parameters such as inspiratory time and inspiratory pause, are then used to ventilate the patient and deliver either oxygen or a combination of oxygen with any of air, helium, nitrous oxide, nitric oxide, and anesthetics. Because the ventilation distribution ratio is improved with the method of this invention, a more efficient and effective mass transfer occurs at the blood/gas interface within the lungs. Further,

the mean lung pressure is reduced to minimize interference with cardiac output.

Description of the Drawings

The structure, operation and advantages of the presently preferred embodiment of this invention will become further apparent upon consideration of the following description, taken in conjunction with the accompanying drawings, wherein,

Fig. 1 is a schematic view of an open loop ventilation system capable of providing flowrate waveform shaping during mechanical inspiratory;

Fig. 2 is a schematic view of a closed loop ventilation system capable of obtaining flowrate waveform shaping during mechanical inspiratory;

Fig. 3 is a graphical depiction of compliance curves for normal and diseased lungs wherein "FRC" is the functional residual capacity and "PEEP" is positive end expiratory pressure;

Fig. 4 is a schematic electrical circuit depicting an electrical analogy to the respiratory pathways formed by the bronchi and lungs of a patient, which is utilized to provide mathematical modeling of the effects of resistance and compliance on distribution of pulmonary ventilation;

Fig. 5 is a table of a computer simulation for normal and healthy lung configurations with equal resistances, compliances and time constants wherein:

R_r = 6 cm H_2O/l/s

C_r = 0.025 l/cm H_2O

R_l = 6 cm H_2O/l/s

C_l = 0.025 l/cm H_2O

Fig. 6 is a table of a computer simulation of lungs having equal resistances, unequal compliances and unequal time constants, wherein:

R_r = 6 cm H_2O/l/s

C_r = 0.0125 l/cm H_2O

R_l = 6 cm H_2O/l/s

C_l = 0.025 l/cm H_2O

Fig. 7 is a table of a computer simulation of lungs having unequal resistances, equal compliances and unequal time constants, wherein:

R_r = 6 cm H_2O/l/s

C_r = 0.025 l/cm H_2O

R_l = 12 cm H_2O/l/s

C_l = 0.025 l/cm H_2O

Fig. 8 is a table of a computer simulation of lungs having unequal resistances and unequal time constants, where the compliance of the right lung is less than that of the left lung, and wherein:

R_r = 6 cm H_2O/l/s

C_r = 0.0125 l/cm H_2O

R_l = 12 cm H_2O/l/s

C_l = 0.025 l/cm H_2O

Fig. 9 is a table of a computer simulation of lungs similar to those of Fig. 8 except with the compliance of the right lung being greater than the compliance of the left lung and unequal time constants, wherein:

R_r = 6 cm H_2O/l/s

C_r = 0.0375 l/cm H_2O

R_l = 12 cm H_2O/l/s

C_l = 0.0125 l/cm H_2O

Fig. 10 is a table of a computer simulation of lungs which cannot be characterized as "normal and healthy" but whose abnormalities do not manifest themselves as inequalities in time constants. The inequalities in resistances and compliances are such that the time constants of the right and left lungs are equal, and wherein:

R_r = 6 cm H_2O/l/s

C_r = 0.025 l/cm H_2O

R_l = 12 cm H_2O/l/s

C_l = 0.0125 l/cm H_2O

Fig. 11 is a condensed table of the results of the computer simulations shown in Figs. 5-10 in which the qualitative trends and effects on different lung configuration types is emphasized in narrative form.

Detailed Description of the Invention

The overall objectives of this invention are to improve the mass transfer rate and efficiency at the blood/gas interface of the lungs in both directions, i.e. removal of carbon dioxide and anesthetics and inflow of oxygen and anesthetics, while minimizing the mean or average pressure in the lungs during ventilation. In order to achieve these objectives, an analysis is disclosed resulting in the grouping of a number of lung types into three general, main classes. Algorithms are provided to permit a determination in a clinical setting of the particular classification for the

lungs of a given patient. Finally, a number of new inspiratory waveforms are disclosed which can be utilized with other ventilatory parameters to ventilate a patient with a particular lung classification to achieve an improved ventilation distribution ratio while minimizing mean lung pressure.

The following discussion is divided into sections directed to the lung classification analysis, clinical determination of the lung class of a particular patient, and, the selection and use of appropriate inspiratory waveforms and other ventilatory parameters for different lung classes.

Development of Lung Classification

With reference initially to the bottom portion of Fig. 1, a schematic depiction is provided of the respiratory passageways of a patient who has been intubated with an endotracheal tube 10 connected to a Y-piece 12. The endotracheal tube 10 is inserted within the trachea 14 of the patient, and a cuff 16 provided on the exterior surface of endotracheal tube 10 is inflated to create a seal with the trachea 14. As described below, one or more sensors 18 sample pressure and gas composition at sampling ports located at the distal tip 20 of the endotracheal tube 10 to provide measurements of pressure and end-tidal carbon dioxide content. One type of endotracheal tube 10 suitable for use herein is a "Hi-Lo" endotracheal tube commercially available from Mallinckrodt. Such tube includes

sampling ports at the distal tip which can be pneumatically connected to pressure sensors.

For purposes of the present discussion, the left bronchus 22 and left lung 24 will be referred to as one respiratory passageway, and the right bronchus 26 and right lung 28 forms another respiratory passageway. The bronchi 22, 26 meet at the carina 29 where the distal tip 20 of the endotracheal tube 10 is positioned. The term "resistance" as used herein is meant to refer to the flow resistance or restriction within each respiratory passageway. The term "compliance" refers to the flexibility or elasticity of the left and right lungs 24, 28 as they expand and contract during inspiration.

Development of the lung classes of this invention began with a computer model based on the mathematical model first suggested by Otis et al. in Mechanical Factors and Distribution of Pulmonary Ventilation, Journal of Applied Physiology 8:427, 1956. The work of Otis, et al. established that an electrical analogy could be employed to model the behavior of lungs wherein compliance equals capacitance, and flow resistance equals electrical resistance. Thus, the diagram depicted in Fig. 4 illustrating an electrical circuit with resistances R_{ett}, R_i and R_t, and capacitances C_i and C_r, with an input I(t), is electrically analogous to the respiratory airways of an intubated patient. The resistance R_{ett} is analogous to the flow resistance within an endotracheal tube, the resistances R_i and

R_r are analogous to the flow resistances within the respective bronchi of a patient, and, the capacitances C_l and C_r are analogous to the compliances of the left and right lungs.

A computer program was developed to simulate and analyze the effects of inspiratory waveform shape, inspiratory time (T_i), inspiratory pause (IP) and tidal volume (VT) during mechanical ventilation. In order to utilize the model proposed by Otis et al. and shown in Fig. 4, it was assumed that compliances and flow resistances are linear, particularly in situations where the total lung volume is less than two (2) liters above functional residual capacity (FRC) and the inspiratory flowrates are less than 80 liters per minute. The term "functional residual capacity," or FRC, refers to the volume of air left in the lungs after exhalation.

With reference to Fig. 3, the propriety of assuming linear compliances and resistances is graphically depicted. The lung compliance curve for a healthy, anesthetized patient in the supine position is a highly skewed sigmoid with a wide linearly sloping portion that flattens out at the top of the curve as the elastic limit of the lungs is approached. See Nunn, J.F. Applied Respiratory Physiology (Third Edition), London, Butterworths 1987. The inflection point where the compliance curve departs from linearity is approximately at the 30 cm H_2O and 2.5 liters above FRC coordinate, for healthy, anesthetized patients in a supine position. Accordingly, the assumption that compliance is linear for healthy

anesthetized patients in a supine position, for tidal volumes not exceeding 2 liters, is accurate.

With respect to patients having lungs with some pathology, or, indeed, serious medical conditions, additional curves are provided in Fig. 3 depicting volume vs. pressure plots for patients having emphysema, asthma and acute respiratory distress syndrome. It can be observed that the compliance curves still retain their skewed sigmoidal shape although the scale and the degree of skew are different. Therefore, the assumption of a linear compliance for these "abnormal" lungs can also be made, provided the volume in the lung is below the inflection point. As depicted in Fig. 3, the inflection points of the compliance curves for different lung pathologies follow a roughly diagonal locus that runs from the upper left to the bottom right of the volume vs. pressure plot. As a practical matter, the inflection point locus implies that a less compliant lung will top its curve at a lower volume above FRC compared to a normal lung. Because it is less compliant, the stiffer lung will generally receive less volume than a more compliant lung in proportion to the ratio of the compliances between the two lungs. Consequently, the very nature of the less compliant lung tends to prevent it from topping its curve and thus stay within the linear compliance region. Conversely, the more compliant lung accepts more volume but also tops its curve at a higher volume above FRC and will thus stay within the linear portion of its compliance curve for a

larger volume range. Accordingly, the assumption of linear compliances and resistances for the various types of lung conditions depicted in Fig. 3 is valid and practically useful within the parameters of total lung volume less than 2 liters above FRC, and inspiratory flowrates less than 80 liters per minute.

As noted above, the computer model is intended to simulate and analyze the effects of (1) inspiratory waveform shape, (2) inspiratory time, T_I, (3) inspiratory pause, (IP), and (4) tidal volume, (VT) during mechanical ventilation on lungs having a variety of resistance and compliance parameters. Prior to this invention, four inspiratory waveforms had been utilized in ventilation and anesthesia apparatus which can be described in equation form as follows:

Constant Flowrate:

$$Q_{ett}(t) = \frac{VT}{T_i} \quad (1)$$

Increasing Flowrate:

$$Q_{ett}(t) = \frac{2VT}{T_i^2} \cdot t \quad (2)$$

Decreasing Flowrate:

$$Q_{ett}(t) = -\frac{2VT}{T_i^2} \cdot t + 2\frac{VT}{T_i} \quad (3)$$

Half-Sine (0-π) Flowrate:

$$Q_{ett}(t) = \frac{\pi VT}{2T_i} \cdot \sin\left(\frac{\pi}{T_i} \cdot t\right) \quad (4)$$

Where: $Q_{ett}(t)$ = total flowrate at the trachea, or endotracheal tube, over time

VT = tidal volume

T_i = inspiratory time

t = time

In addition to these four known waveforms, a number of new flowrate waveforms have been discovered which, in at least some instances, produce improved results as discussed in more detail below.

Quarter sine ($\pi/2 - \pi$)

$$Q_{ect}(t) = \frac{\pi VT}{2T_i} \sin\left(\frac{\pi}{2} + \frac{\pi}{2T_i} \cdot t\right) \quad (5)$$

Shifted Quarter Sine ($\pi - 3\pi/2$)

$$Q_{ect}(t) = \frac{VT}{T_i \cdot (1-\frac{2}{\pi})}\left(1 + \sin(\pi + \frac{\pi}{2T_i} t)\right) \quad (6)$$

Trapezoid

$$Q_{ect}(0 \le t < \frac{T_i}{2}) = \frac{4VT}{3T_i} \quad (7)$$

$$Q_{ect}(\frac{T_i}{2} \le t \le T_i) = -\frac{8VT}{3T_i^2} \cdot \left(t - \frac{T_i}{2}\right) + \frac{4VT}{3T_i} \quad (8)$$

Decaying Exponential ($\tau = T_i/5$)

$$Q_{ect}(t) = \frac{VT}{0.198652T_i} e^{-\frac{5t}{T_i}} \quad (9)$$

Decaying Exponential ($\tau = T_i/n$)

$$Q_{ect}(t) = f[VT, T_i]\, e^{\frac{-nt}{T_i}} \quad (10)$$

Rising Exponential ($\tau = T_i/5$)

$$Q_{ect}(t) = \frac{0.033918\ VT}{T_i} e^{\frac{5t}{T_i}} \quad (11)$$

Rising Exponential ($\tau=T_i/n$)

$$Q_{ett}(t) = f[VT, T_i]\, e^{\frac{nt}{T_i}} \quad (12)$$

t^2

$$Q_{ett}(t) = \frac{3VT \cdot t^2}{T_i^3} \quad (13)$$

t^3

$$Q_{ett}(t) = \frac{4VT \cdot t^3}{T_i^4} \quad (14)$$

t^n

$$Q_{ett}(t) = \frac{(n+1)\,VT}{T_i^{n+1}} \cdot t^n \quad (15)$$

Where:

$Q_{ett}(t)$	=	total flowrate at the trachea, over time
VT	=	tidal volume
T_i	=	inspiratory time
τ	=	time constant of flowrate change
n	=	any number
$f[VT, T_i]$	=	a constant which is a function of VT and T_i
t	=	time

Additionally, an ideal increasing exponential flowrate waveform is given by the following relationship:

$$Q_{ett}(t) = Ae^{\alpha t} \quad (16)$$

Where:

$$A = \frac{\alpha}{e^{\alpha T_i} - 1} \; VT \quad (17)$$

$$\alpha = \frac{|C_l - C_r|}{C_r C_l |(R_l - R_r)|} \quad (18)$$

C_r	=	right lung compliance
C_l	=	left lung compliance
R_r	=	right lung resistance
R_l	=	left lung resistance
VT	=	tidal volume
T_i	=	inspiratory time
$Q_{ett}(t)$	=	total flowrate of trachea or endotracheal tube, over time
t	=	time

It should be noted that equations 9 and 11 listed above, i.e. for decaying exponential and rising exponential flowrate waveforms, employ a time constant equal to the inspiratory time divided by 5 (T_i/5.) This was an arbitrary selection utilized in the computer model for purposes of comparison with other waveforms. Other time constants of the flowrate decay can be utilized, e.g. $\tau = T_i/n$, where n can be essentially any number.

Equations 10 and 12 depict decaying exponential and rising exponential flowrate waveforms where $\tau=T_i/n$, and wherein the constant f [VT, T_i] is a function of tidal volume (VT) and inspiratory time (T_i).

In addition to the flowrate inspiratory waveform noted above, shaping of a particular input to a patient can be achieved with pressure inspiratory waveforms. With waveforms of this type, the clinician is concerned with determining the peak pressure required during each breath to deliver the desired tidal volume (VT) to the patient within a chosen inspiratory time (T_i). For purposes of the computer modeling employed in this invention to obtain data for lung classification, as described below, three pressure inspiratory waveforms were employed which can be expressed in equation form as follows:

Constant Pressure

$$P_c(t) = P_c \qquad (19)$$

Where: P_c is constant during inspiration and is the pressure at the carina

t = time

Increasing Pressure

$$P_c(t) = mt \qquad (20)$$

Where: m = ramp slope

t = time

P_c = pressure at the carina

Rising Exponential Pressure ($\tau=T_i/n$)

$$P_c(t) = P_o e^{\frac{nt}{T_i}} \quad (21)$$

Rising Exponential Pressure ($\tau=T_i/5$)

$$P_c(t) = P_o e^{\frac{5t}{T_i}} \quad (22)$$

t^2

$$P_c(t) = P_o \left(\frac{t}{T_i}\right)^2 \quad (23)$$

t^3

$$P_c(t) = P_o \left(\frac{t}{T_i}\right)^3 \quad (24)$$

Where: T_i = inspiratory time

P_o = an arbitrarily set starting point for the pressure waveform which is iteratively adjusted as the pressure waveform is maintained, and as the actually delivered tidal volume is measured, until the desired tidal volume is obtained

P_c = pressure at the carina

n = any number

τ = time constant of pressure rise

t = time

Pressure and flowrate waveforms with time derivatives which are themselves strong functions of time, such as set forth above in equations 11-15 and 21-24, are desirable. Equations 23 and 24, for example, can be written in more general form as follows:

t^n

$$P_c(t) = P_o\left(\frac{t}{T_i}\right)^n \qquad (25)$$

Where: T_i = inspiratory time

P_o = an arbitrarily set starting point for the pressure waveform which is iteratively adjusted as the pressure waveform is maintained, and as the actually delivered tidal volume is measured, until the desired tidal volume is obtained

P_c = pressure at the carina

n = any number greater than 1

t = time

A binary (normal/abnormal) approach was used in mapping out all possible combinations of C_r, C_l, R_r and R_l. Initially, it was noted that a total of 16 different combinations of lung types are possible considering the compliances C_r and C_l of each lung, and flow resistances R_r and R_l of each respiratory pathway, as independent variables. For ease of notation, lungs with normal compliance and resistance are denoted by C and R, respectively. Abnormal lungs are denoted by C/n and mR where n and m are usually greater than 1, since clinical abnormalities normally manifest themselves as reduced compliance and increased resistance. Using these notations, the following table can be generated listing the 16 possible lung combinations:

R_r	C_r	R_l	C_l	Lung Type
R	C	R	C	1
R	C	R	C/n	2
R	C	mR	C	3
R	C	mR	C/n	5
R	C/n	R	C	2
R	C/n	R	C/n	1
R	C/n	mR	C	4
R	C/n	mR	C/n	3
mR	C	R	C	3
mR	C	R	C/n	4
mR	C	mR	C	1
mR	C	mR	C/n	2
mR	C/n	R	C	5
mR	C/n	R	C/n	3
mR	C/n	mR	C	2
mR	C/n	mR	C/n	1

The last line of the above column entitled "Lung type" refers to a reduced list of six lung combinations which can be distilled from the 16 possible combinations, due to functional similarities. For example, if compliances are similar but one flow resistance is twice the other, it does not matter if the higher resistance is in the right or left lung. Further, because compliance and resistance are independent of each other, the actual magnitude of the compliance compared to the resistance is not significant,

and vice versa. In tabular form, the "distilled" or reduced list of possible lung configurations is given below as follows:

Lung Type	Comparative Resistances	Comparative Compliances
1	$R_r = R_l$	$C_r = C_l$
2	$R_r = R_l$	$C_r < C_l$
3	$R_r < R_l$	$C_r = C_l$
4	$R_r < R_l$	$C_r < C_l$
5	$R_r < R_l$	$C_r > C_l$
5a	$mR_r = R_l$	$C_r/n = C_l$

The lung type labelled "5a" in the above table refers to a special configuration in which the resistance in the right lung is less than the resistance in the left lung by the same proportion as the compliance in the left lung is less than the compliance in the right lung, i.e. n = m. This category or type of lung is similar to type 1, as discussed in more detail below.

With reference to Figs. 5-10, a computer simulation was performed for each of the lung categories or types 1-5a wherein a number of ventilatory parameters were systematically altered for comparative purposes. Figs. 5-10 correspond to the six lung types 1-5a, respectively. With reference to the top portion of the tables of Figs. 5-10, the categories entitled "Ventilation Parameters" include a reference to "shape," i.e. the waveform shapes utilized, inspiratory time (T_i), tidal volume (VT), and,

inspiratory pause (IP), expressed as a percentage of the inspiratory time. Note that each of the inspiratory flowrate waveforms mentioned above, and three inspiratory pressure waveforms, were incorporated in the analysis. The abbreviations utilized to depict waveform shape in each of Figs 5-10, beginning at the top of the column, are as follows: constant, increasing, decreasing, half-sine (0-π), quarter-sine (π/2-π), trapezoid, decreasing exponential, shifted quarter-sine (π-3π/2) and rising exponential. The three pressure waveforms employed in the computer simulation include constant, increasing and rising exponential.

The heading "Before Pause" utilized at the top of the tables in Figs. 5-10 refers to variables measured at the end of the active inflation period but before exhalation. The quotient V_r/V_l refers to the ratio of the volume of air in each lung at the end of active inflation, which is also defined as the ventilation distribution ratio. The abbreviation MLP refers to the mean lung pressure during active inflation, expressed in centimeters of water. The variables under the heading "End of Inspiration" in Figs. 5-10, refer to variables measured at the end of an inspiration, either with or without an inspiratory pause. R_v (T_l) and MLP are the same as described above. The abbreviation PIP refers to peak inspiratory pressure, expressed in centimeters of water, which is defined as the maximum pressure within the lungs at the end of inspiration. The term Q_{max} is the maximum flowrate for a given flowrate waveform and is expressed in liters per

minute. The term "System τ (s)" refers to the time constant for the entire respiratory system and "iter" refers to the number of breath iterations performed in the computer simulation before a pressure waveform achieves the desired VT.

Still another method of assisting in determining the lung characteristics of a particular patient involves quantification of the effective time constant of the entire respiratory system. In the presently preferred embodiment, a constant pressure waveform (pressure step input of time duration T_i) is applied at the carina and an analysis is undertaken of the resulting flow rate trace at the endotracheal tube. To obtain a constant pressure waveform at the carina, the pressure is sampled at the distal tip and a feedback loop within the apparatus herein is implemented to maintain the pressure thereat to the desired constant value. The flowrate at the distal tip of the endotracheal tube over time ($Q_{ett}(t)$) decays exponentially in response to a pressure step at the carina, with the maximum inspiratory flowrate, Q_{max}, corresponding to the initial flowrate, Q_{ett} (t=0). The point in time at which $Q_{ett}(t) = \exp(-1) \bullet Q_{max}$ ($0.368\ Q_{max}$) corresponds to the time constant of the entire respiratory system, and can be determined by measuring the flow at the endotracheal tube with the flow meter placed thereat.

Alternatively, the effective time constant of the entire respiratory system can also be quantified by an increasing ramp pressure

input at the carina. For an increasing pressure waveform, $Q_{max} = Q_{ex}(T_i)$. The point in time when $Q_{ex}(t)$ reaches $(1 - \exp(-1))\ Q_{max} = (1 - 0.368)\ Q_{max} = 0.632\ Q_{max}$ is the time constant of the entire respiratory system and can be determined in the same way as with the constant pressure technique.

Fig. 11 is a condensed table of the results of the computer simulations depicted in Figs. 5-10. The same definitions noted above are applied to the terms used in Fig. 11, and "R_v" is intended to refer to the ventilation distribution ratio. The results noted in Fig. 11 are expressed in narrative form with an emphasis on the qualitative trends and effects on different lung configuration types. Based upon the pattern of responses of the different lung types to different inspiratory waveforms, the original 16 different combinations of lungs can be further reduced from 6 types of lung combinations, to a total of 3 lung classes, as follows:

Lung Class	Lung Types	Defining Conditions
I	1, 5a	Equal individual time constants
II	2, 4 and 5	Unequal compliance, no restriction on resistance
III	3	Equal compliance, un-equal resistance

Accordingly, based upon the computer modeling depicted in Figs. 5-10 as summarized in narrative form in Fig. 11, all lung configurations can fit into three classes having distinctive differences in their dynamic response

to inspiratory waveform inputs of pressure or flowrate, to an inspiratory pause (IP), and, to the time duration of inspiration (T_i) during mechanical ventilation. In the sections that follow, an explanation is provided as to how to clinically determine which class is correct for the lungs of a given patient, followed by a discussion of the appropriate inspiratory waveform and other ventilatory parameters for that lung class.

Clinical Determination of Lung Class

Referring initially to Figs. 1 and 2, two systems are depicted for introducing a particular inspiratory waveform through the Y-piece 12 and endotracheal tube 10 to the patient. The system 30 of Fig. 1 is a schematic view of an open loop configuration including a computer 32 having an internal control input, depicted graphically by the box 34, which produces an output Q(t) which is the input to a digital to analog converter represented by box 36. The digital to analog converter 36, in turn, produces a corresponding voltage V(t) which is input to what is generically referred to as "interface circuitry" at box 38. This interface circuitry 38 is representative of an element such as a voltage to current driver which is effective to convert the voltage V(t) to a corresponding current I(t), as shown in Fig. 1. The current I(t) is input to a proportional flow control valve 40 which also receives "gas" e.g. oxygen and any of anesthetics, nitrous oxide, nitric oxide, air or helium, among others, from a gas supply

42. The gas is output from the control valve 40 at a flowrate Q(t) to the Y-piece 12 connected to the endotracheal tube 10. An exhalation valve 43 is provided at the output side of the Y-piece 12. During inspiration, including the inspiratory pause, the exhalation valve 43 is closed. During exhalation, valve 43 is opened to allow the patient to exhale.

The system 44 of Fig. 2 is a diagrammatic representation of a closed loop configuration in which a control input $Q_d(t)$ from a computer depicted as box 46 is input to a comparator 48 which is connected to a proportional flow control valve 50. This flow control valve 50 receives a supply of oxygen, with or without anesthetics, nitrous oxide, nitric oxide, air, or helium, among others, from a gas supply 52. The control valve 50 discharges the gas to a flowrate sensor 54 which, in turn, inputs a gas flow Q(t) via line 55 to the Y-piece 12 connected to endotracheal tube 10. The system 44 of Fig. 2 has a feedback loop which includes the flowrate sensor 54 and line 56 connected to the comparator 48. The flowrate sensor 54 is effective to sense the actual flow of gas discharged from control valve 50 and provide a signal $Q_m(t)$ to the comparator 48 where it is compared with the input signal $Q_d(t)$ to adjust the signal input to the flow control valve 50 so that the appropriate flow rate is supplied to the patient. For purposes of illustration, the flow $Q_d(t)$ from box 46 is given a positive "+" sign and the input $Q_m(t)$ is given a "-" sign.

Although not depicted in Fig. 2, this same type of feedback loop is employed in the generation of pressure inspiratory waveforms except that pressure is sampled at the distal tip 20 of the endotracheal tube 10. This time-varying pressure sample is input to the comparator 48 where it is compared to a reference control signal in order to match the delivered pressure to the desired pressure waveform.

Either of the systems 30 or 44 depicted in Figs. 1 and 2 can be utilized to input an inspiratory flowrate or pressure waveform of desired configuration to the endotracheal tube 10, and are effective to vary other ventilatory parameters such as inspiratory time (T_i), inspiratory pause (IP), and tidal volume (VT), as desired. It is contemplated that many commercially available ventilators and anesthesia machines can be utilized for this purpose, and it should be understood that the particular configuration of systems 30, 44 is given for purposes of illustration only and should in no way be considered as limiting the scope of this invention.

Before describing particular lung identification algorithms, it should be noted that certain assumptions have been made regarding operation of the systems 30 and 44. First, it is assumed that real-time end-tidal carbon dioxide values from breath to breath can be sensed through the sampling port 18 at the distal tip of the endotracheal tube 10, and supplied to the computers 32 or 46. Secondly, as described below in connection with a discussion of one algorithm wherein the pattern of ventilation is

successively changed, it is assumed that a change in the ventilation pattern for two consecutive breaths does not disrupt the ventilation of the patient. Finally, it is assumed that the production of carbon dioxide within the lungs will remain constant over a duration of ten breaths (e.g. about 60 seconds) such that the end-tidal carbon dioxide detected during that ten breath period will be solely a function of the ventilation distribution ratio, i.e. the relative proportion or ratio of distribution of gas to each lung.

With reference to Fig. 11, it is observed that increased inspiratory time, T_i, produces an improved ventilation distribution ratio for Class III lungs while having no benefits for Class I lungs or even a worsening effect for Class II lungs. For example, from Fig. 7, using a constant flowrate waveform, it is seen that lengthening of the inspiratory time from 2.0 to 4.0 seconds, while keeping all other parameters constant, results in an improvement of the ventilation distribution ratio, $R_v(T_i)$, from 1.078 to 1.038. The control software of the computers 32 and 46 associated with systems 30 and 44 is therefore programmed to increase the inspiratory time T_i while maintaining the same tidal volume and inspiratory waveform for ten consecutive breaths. In a Class III lung, it is believed that the system operator will observe a decrease in end-tidal carbon dioxide in the exhalation following ventilation with increased inspiratory time because of the better distribution of ventilation with the Class III lung. On the other hand, it is believed that an increase in inspiratory time yields no

significant change in end-tidal carbon dioxide readings with a Class I lung, and can even increase the end-tidal carbon dioxide in Class II lungs. As a result, a Class III lung is positively identified with this algorithm.

Referring again to the narrative summary provided in Fig. 11, it is noted that an inspiratory pause, (IP), improves the ventilation distribution ratio for a Class III lung while having no effect on Class I lungs, and possibly a deteriorating effect on the ventilation distribution ratio for a Class II lung. With reference again to Fig. 7, it is noted that a rising exponential flowrate inspiratory waveform provides the most dramatic improvement in ventilation distribution ratio for a Class III lung using an inspiratory pause, i.e. from a level of 1.275 to 1.032. The ventilation control software of computers 32 and 46 associated with systems 30, 44 respectively, is therefore programmed to employ an exponential flowrate waveform with an inspiratory pause. For example, the patient could be ventilated with a rising exponential flowrate waveform having an inspiratory time of two seconds, without an inspiratory pause, followed by the same waveform containing a 25% inspiratory pause, e.g. 1.5 seconds active inflation, and 0.5 second pause for ten breaths or one minute. In a Class III lung, it is believed that a drop of end-tidal carbon dioxide would be sensed following ventilation with the inspiratory pause compared to the previous waveform without the inspiratory pause. It is further believed that no lowering of end-tidal carbon dioxide is seen with

a Class I lung, and Class II lungs will produce either no change or an increase in end-tidal carbon dioxide.

Another algorithm can be utilized for lung classification in which inspiratory waveforms are changed between consecutive breaths, and the following discussion is based on a belief of the clinical results of the use of same. For example, the narrative table in Fig. 11 indicates that if a constant pressure waveform is immediately followed by ventilation for ten breaths or one minute with a rising exponential flowrate waveform of the same tidal volume and the same inspiratory time, a rise in end-tidal carbon dioxide follows ventilation with the rising exponential flowrate waveform for a Class III lung. No change in end-tidal carbon dioxide is produced with a Class I lung, under these ventilation conditions, and Class II lungs produce a decrease in end-tidal carbon dioxide. The computers 32 and 46 associated with systems 30, 44 respectively, are therefore programmed to first introduce a constant pressure waveform and then a rising exponential flowrate waveform with the tidal volume and inspiratory time being maintained constant. When using system 44, it is recommended that the constant pressure waveform be preceded by several constant pressure breaths so that the feedback loop can be set to produce the desired tidal volume before end-tidal carbon dioxide is measured.

The foregoing discussion has been primarily directed to lung classification algorithms intended to distinguish Class III lungs from Class

I and II lungs. As discussed below, although patients having Class I or II lungs can be appropriately ventilated with many of the same inspiratory waveforms, in some instances it may be desirable to distinguish the patients with Class I and II lungs. For this purpose, it is noted that the computer simulation performed to generate the data in Figs. 5-10 was predicated upon the assumption that the pressure in each lung of Class I lungs is substantially equal during the entire inflation period. As such, if an inspiratory flowrate waveform is followed by an inspiratory pause, it is believed there will be no gas redistribution or "pendelluft" in patients with Class I lungs. The term pendelluft refers to a redistribution of gas from one lung to the other in the event the pressure within one lung is greater than the other. If this occurs, the gas within the higher pressure lung will flow to the lung of lower pressure so that the pressure between the two lungs is substantially equalized. In the absence of pendelluft, the pressure at the carina, as sensed at the sampling port 18 at the distal tip of the endotracheal tube 10, drops sharply during an inspiratory pause to a flat plateau.

It is further believed that in a Class III lung, on the other hand, where pressures are not generally equal in each lung at the end of active inflation, there is gas redistribution during the inspiratory pause according to the pressure differential between the lungs. Such redistribution of gas flow during the inspiratory pause causes the pressure

at the carina to decay in an exponential fashion to a plateau rather than falling steeply to a plateau as in Class I lungs. Such gas redistribution and exponential decay in pressure at the carina therefore provides a means of differentiation between Class I and Class III lungs.

Selection Of And Ventilation With An Appropriate Flowrate Waveform

The purpose of selecting an appropriate inspiratory waveform in lungs of unequal time constant, i.e. different compliances and/or resistances, is to match the ventilation or gas flowrate to the perfusion or blood flowrate. As discussed above, the presence of different gas volumes in the right and left lung can create an undesirable ventilation/perfusion ratio mismatch which degrades the rate of gas exchange, and the efficiency of gas exchange, at the blood/gas interface within the lungs. While the body's compensatory mechanisms shunt the blood flow to favor the better ventilated lung, there is a limit to that self-regulatory action which can be depressed by some anesthetics. The objective, therefore, is to obtain a ventilation distribution ratio which is as close to unity as possible, e.g.:

$$R_v(T_i) = V_r(T_i)/V_l(T_i)$$

$$= 1$$

In addition to obtaining a ventilation distribution ratio as close to 1 as possible, inspiratory waveforms must be chosen to minimize the mean lung

pressure or time-averaged pressure experienced by the lungs during an inspiratory cycle. As discussed above, higher mean lung pressures during mechanical ventilation can reduce the cardiac output by interfering with the filling and emptying of the heart since the lungs and heart both reside within the chest cavity. With these factors in mind, appropriate ventilation conditions for each lung can be summarized as follows.

Class I Lungs

Class I lungs have been defined above as having equal time constants for both respiratory pathways. That is, the product of the resistance and compliance (RC) is equal for both the right and left respiratory pathways. In Class I lungs, the ventilation distribution ratio is independent of the shape of the inspiratory waveform, independent of the duration of inspiration, T_i, and is not affected by the presence or duration of an inspiratory pause, IP. The ventilation distribution ratio is determined by the compliance ratio (C_r/C_l) only. While it is contemplated that a number of inspiratory waveforms would be suitable for use with Class I lungs, it is noted that the increasing exponential waveform produces the lowest mean lung pressure over time in Class I lungs, which makes its use potentially the most desirable. It is also noted that an inspiratory pause increases the mean lung pressure within Class I lungs, and is therefore not recommended.

Class II Lungs

A number of recommendations regarding waveform shape, inspiratory time and inspiratory pause can also be made for Class II lungs (unequal compliance, equal or unequal resistance) based upon the data compiled in Figs. 5-11. As with Class I lungs, the rising exponential waveform produces the lowest mean pressure within Class II lungs and is probably the best choice, although other waveforms are useful. Regardless of the shape of the inspiratory waveform, a shorter inspiratory time tends to produce a more even ventilation distribution ratio and is recommended for Class II lungs. An inspiratory pause worsens the ventilation distribution ratio and increases the mean lung pressure within Class II lungs, and is therefore not recommended.

Class III Lungs

With respect to Class III lungs (equal compliance, unequal resistance), a selection of different waveforms is probably best made in a clinical setting with the following guidelines. It has been found that a rising exponential flowrate waveform produces the lowest mean lung pressure within patients having Class III lungs, but the resulting ventilation distribution ratio is most uneven. A constant pressure waveform, on the other hand, produces the highest level of mean lung pressure for Class III lungs but also results in the most even ventilation distribution ratio. The

selection of one or the other of these waveforms will therefore depend on the clinician's evaluation of the condition of a particular patient.

It is also apparent from the data in Figs. 5-10 that an inspiratory pause, regardless of the type of waveform, improves the ventilation distribution ratio and is strongly recommended for Class III lungs. Further, increased inspiratory time also evens the ventilation distribution ratio and produces a lower mean lung pressure in Class III lungs. Accordingly, a constant pressure or a decaying exponential flowrate waveform with a longer inspiratory time, and an inspiratory pause, produce good ventilation distribution in Class III lungs.

The methodology of this invention therefore involves a clinical determination or identification of the class of the lungs of a particular patient, followed by the selection of an appropriate inspiratory waveform, inspiratory pause (if any) and inspiratory time to produce a ventilation distribution ratio as close to unity as possible while minimizing the mean lung pressure. This methodology improves the mass transfer rate and efficiency at the blood/gas interface within the lungs to achieve better delivery of oxygen and anesthetics into the blood stream and removal of carbon dioxide and anesthetics therefrom during artificial ventilation.

While the invention has been described with reference to a preferred embodiment, it will be understood by those skilled in the art that various changes may be made and equivalence may be substituted for

elements thereof without departing from the scope of the invention. In addition, many modifications can be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

1. A method of artificially ventilating a patient, comprising:

determining the class of the lungs of the patient;

selecting an appropriate inspiratory waveform for the particular lung class of such patient;

ventilating such patient with the selected inspiratory waveform.

2. The method of claim 1 in which said step of determining the class of the lungs comprises determining whether the patient has lungs with equal individual time constants, lungs of unequal compliance with no restriction on resistance, or lungs with equal compliance and unequal resistance.

3. The method of claim 1 in which said step of determining the class of the lungs comprises:

ventilating the patient with an inspiratory waveform having a first inspiratory time;

thereafter ventilating the patient with said inspiratory waveform for a second inspiratory time which is greater than said first inspiratory time throughout a selected time period or number of breaths while maintaining tidal volume constant;

sensing the end-tidal carbon dioxide concentration of the gas exhaled by the patient following each of said inspiratory waveforms, and comparing said sensed concentration of end-tidal carbon dioxide.

4. The method of claim 3 in which said step of thereafter ventilating the patient includes thereafter ventilating the patient with said inspiratory waveform for a second inspiratory time which is greater than said first inspiratory time for at least ten breaths or about one minute while maintaining tidal volume constant.

5. The method of claim 1 in which said step of determining the class of the lungs, comprises:

ventilating the patient with an inspiratory waveform without inspiratory pause;

thereafter ventilating the patient with said inspiratory waveform containing an inspiratory pause while maintaining tidal volume constant for a selected period;

sensing the end-tidal carbon dioxide concentration of the gas exhaled by the patient following each of said inspiratory waveforms, and comparing said sensed concentration of end-tidal carbon dioxide.

6. The method of claim 5 in which said steps of ventilating the patient comprises ventilating the patient with a rising exponential flowrate inspiratory waveform.

7. The method of claim 1 in which said step of determining the class of the lungs, comprises:

ventilating the patient with a constant pressure inspiratory waveform having a selected tidal volume and inspiratory time;

thereafter ventilating the patient with a rising exponential flowrate inspiratory waveform having the same tidal volume and inspiratory time as said constant pressure waveform for a selected time period;

sensing the end-tidal carbon dioxide concentration of the gas exhaled by the patient following each of said inspiratory waveforms, and comparing said sensed concentrations of end-tidal carbon dioxide.

8. The method of claim 1 in which said step of determining the class of the lungs comprises:

ventilating the patient with an inspiratory waveform including an inspiratory pause, said inspiratory waveform being delivered through an endotracheal tube with which the patient is intubated;

measuring the pressure at the carina.

9. The method of claim 8 in which said step of measuring the pressure at the carina comprises sensing the pressure through a sampling port at the distal tip of the endotracheal tube.

10. The method of claim 1 in which said step of determining the class of the lungs comprises:

ventilating the patient with an inspiratory waveform including an inspiratory pause, said inspiratory waveform being delivered through an endotracheal tube with which the patient is intubated;

sensing the presence of a redistribution of gas from one lung of the patient to the other during the inspiratory pause of said inspiratory waveform by measuring the slope of pressure at the carina over time.

11. The method of claim 1 in which said step of determining the class of the lungs comprises:

sensing the intratracheal pressure trace at a beginning segment of exhalation;

sensing the intratracheal pressure trace at an ending segment of exhalation;

taking the natural logarithm of each of said intratracheal pressure traces over time, and comparing the resulting slopes to one another.

12. The method of claim 1 in which said step of determining the class of the lungs comprises:

ventilating the patient with an inspiratory waveform;

measuring the pressure at the distal tip of an endotracheal tube with which the patient is intubated during expiration;

examining the time constants of the resulting intratracheal pressure trace obtained from such pressure measurement.

13. The method of claim 1 in which said step of selecting the appropriate inspiratory waveform comprises selecting an inspiratory waveform which produces a ventilation distribution ratio closest to unity while minimizing mean lung pressure.

14. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a quarter-sine ($\pi/2$ - π) flowrate waveform defined as follows:

$$Q_{ett}(t) = \frac{\pi VT}{2T_i} \sin\left(\frac{\pi}{2} + \frac{\pi}{2T_i} \cdot t\right)$$

Where: $Q_{ett}(t)$ = total flowrate at the trachea or endotracheal tube, over time

VT = tidal volume

T_i = inspiratory time

t = time

15. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a shifted quarter-sine (π - $3\pi/2$) flowrate waveform defined as follows:

$$Q_{ett}(t) = \frac{VT}{T_i \cdot (1-\frac{2}{\pi})}\left(1 + \sin(\pi + \frac{\pi}{2T_i} t)\right)$$

Where: $Q_{ett}(t)$ = total flowrate at trachea or endotracheal tube, over time

VT = tidal volume

T_i = inspiratory time

t = time

16. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a trapezoid flowrate waveform defined as follows:

$$Q_{ecc}\left(0 \le t < \frac{T_i}{2}\right) = \frac{4VT}{3T_i}$$

$$Q_{ecc}\left(\frac{T_i}{2} \le t \le T_i\right) = -\frac{8VT}{3T_i^2} \cdot \left(t - \frac{T_i}{2}\right) + \frac{4VT}{3T_i}$$

Where:

Q_{ett}	=	total flowrate at trachea or endotracheal tube, over time
VT	=	tidal volume
T_i	=	inspiratory time
t	=	time

17. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a decaying exponential ($\tau=T_I/n$) flowrate waveform defined as follows:

$$Q_{ett}(t) = f[VT, T_I]\, e^{\frac{-nt}{T_I}}$$

Where:
- $Q_{ett}(t)$ = total flowrate at trachea or endotracheal tube, over time
- VT = tidal volume
- T_I = inspiratory time
- τ = time constant of flowrate decay
- n = any number
- t = time

18. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a decaying exponential ($\tau = T_i/5$) flowrate waveform defined as follows:

$$Q_{ett}(t) = \frac{VT}{0.198652T_i} e^{-\frac{5t}{T_i}}$$

Where: $Q_{et}(t)$ = total flowrate at trachea or endotracheal tube, over time

VT = tidal volume

T_i = inspiratory time

τ = time constant of flowrate decay

t = time

19. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a rising exponential ($\tau=T_i/n$) flowrate waveform defined as follows:

$$Q_{ett}(t) = f[VT, T_i]\, e^{\frac{nt}{T_i}}$$

Where:
- $Q_{ett}(t)$ = total flowrate at trachea or endotracheal tube, over time
- VT = tidal volume
- T_i = inspiratory time
- τ = time constant of flowrate rise
- n = any number
- t = time

20. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a rising exponential ($\tau = T_i/5$) flowrate waveform defined as follows:

$$Q_{etc}(t) = \frac{0.033918\ VT}{T_i}\ e^{\frac{5t}{T_i}}$$

Where:
- $Q_{et}(t)$ = total flowrate at trachea or endotracheal tube, over time
- VT = tidal volume
- T_i = inspiratory time
- τ = time constant of flowrate rise
- t = time

21. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a flowrate waveform defined as follows:

$$Q_{ett}(t) = \frac{3VT \cdot t^2}{T_i^3}$$

Where: $Q_{ett}(t)$ = total flowrate at trachea or endotracheal tube, over time

VT = tidal volume

T_i = inspiratory time

t = time

22. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a flowrate waveform defined as follows:

$$Q_{ett}(t) = \frac{4VT \cdot t^3}{T_i^4}$$

Where: $Q_{ett}(t)$ = total flowrate at trachea or endotracheal tube, over time

VT = tidal volume

T_i = inspiratory time

t = time

23. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a flowrate waveform defined as follows:

$$Q_{ett}(t) = \frac{(n+1)\,VT}{T_i^{n+1}} \cdot t^n$$

Where: $Q_{ett}(t)$ = total flowrate at trachea or endotracheal tube, over time

VT = tidal volume

T_i = inspiratory time

t = time

n = any number

24. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting an ideal increasing exponential flowrate waveform, defined as follows:

$$Q_{ett}(t) = Ae^{\alpha t}$$

Where:

$$A = \frac{\alpha}{e^{\alpha T_i}-1} \quad VT$$

$$\alpha = \frac{|C_l - C_r|}{C_r C_l |(R_l - R_r)|}$$

C_r = right lung compliance

C_l = left lung compliance

R_r = right lung resistance

R_l = left lung resistance

VT = tidal volume

$Q_{ett}(t)$ = total flowrate a trachea or endotracheal tube, over time

T_i = inspiratory time

t = time

25. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a constant pressure waveform, defined as follows:

$$P_c(t) = P_c$$

where: P_c is constant during inspiration and is the pressure at the carina which is iteratively adjusted while the constant pressure waveform is maintained until the desired tidal volume is obtained

t = time

26. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a linearly increasing pressure waveform as follows:

$$P_c(t) = mt$$

where: m = ramp slope which is iteratively adjusted as the pressure waveform is maintained until the desired tidal volume is obtained

t = time

P_c = pressure at carina

27. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a rising exponential pressure waveform as follows:

$$P_c(t) = P_o e^{\frac{nt}{T_i}}$$

Where:
- T_i = inspiratory time
- P_o = an arbitrarily set starting point for the pressure waveform which is iteratively adjusted as the pressure waveform is maintained, and as the actually delivered tidal volume is measured, until the desired tidal volume is obtained
- P_c = pressure at carina
- n = any number
- t = time

28. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a pressure waveform, t^2, defined as follows:

$$P_c(t) = P_o\left(\frac{t}{T_i}\right)^2$$

Where:

T_i	=	inspiratory time
P_o	=	an arbitrarily set starting point for the pressure waveform which is iteratively adjusted as the pressure waveform is maintained, and as the actually delivered tidal volume is measured, until the desired tidal volume is obtained
P_c	=	pressure at carina
t	=	time

29. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a pressure waveform, t^3, defined as follows:

$$P_c(t) = P_o\left(\frac{t}{T_i}\right)^3$$

Where: T_i = inspiratory time

P_o = an arbitrarily set starting point for the pressure waveform which is iteratively adjusted as the pressure waveform is maintained, and as the actually delivered tidal volume is measured, until the desired tidal volume is obtained

P_c = pressure at carina

t = time

30. The method of claim 1 in which said step of selecting an appropriate inspiratory waveform comprises selecting a pressure waveform, t^n, defined as follows:

$$P_c(t) = P_o\left(\frac{t}{T_i}\right)^n$$

Where: T_i = inspiratory time

P_o = an arbitrarily set starting point for the pressure waveform which is iteratively adjusted as the pressure waveform is maintained, and as the actually delivered tidal volume is measured, until the desired tidal volume is obtained

P_c = pressure at carina

n = any number greater than 1

t = time

31. A method of artificially ventilating a patient, comprising:

determining the class of the lungs of the patient;

selecting an inspiratory waveform having an appropriate shape, inspiratory time and inspiratory pause for the lung class of such patient;

ventilating such patient with the selected inspiratory waveform.

32. The method of claim 31 in which said step of determining the class of the lungs comprises determining whether the patient has lungs with equal individual time constants, lungs of unequal compliance with no restriction on resistance, or lungs with equal compliance and unequal resistance.

33. The method of claim 31 in which said step of selecting an appropriate inspiratory waveform comprises selecting an inspiratory waveform with zero inspiratory pause for lungs with equal individual time constants.

34. The method of claim 31 in which said step of selecting an appropriate inspiratory waveform comprises selecting an inspiratory waveform with a comparatively short inspiratory time for lungs of unequal compliance with no restriction on resistance.

35. The method of claim 31 in which said step of selecting an appropriate inspiratory waveform comprises selecting an inspiratory waveform with zero inspiratory pause for lungs of unequal compliance with no restriction on resistance.

36. The method of claim 31 in which said step of selecting an appropriate inspiratory waveform comprises selecting an inspiratory waveform having an inspiratory pause on the order of about 25% of the inspiratory time for lungs with equal compliance and unequal resistance.

37. The method of claim 31 in which said step of selecting an appropriate inspiratory waveform comprises selecting an inspiratory waveform with a comparatively long inspiratory time for lungs of equal compliance and unequal resistance.

38. The method of claim 31 in which said step of selecting an appropriate inspiratory waveform comprises selecting at least one of the flowrate waveforms, defined as follows:

Quarter sine ($\pi/2$ - π)

$$Q_{ect}(t) = \frac{\pi VT}{2T_i} \sin\left(\frac{\pi}{2} + \frac{\pi}{2T_i}.t\right)$$

Shifted Quarter Sine (π - $3\pi/2$)

$$Q_{ect}(t) = \frac{VT}{T_i.(1-\frac{2}{\pi})}\left(1 + \sin(\pi + \frac{\pi}{2T_i}t)\right)$$

Trapezoid

$$Q_{ect}(0 \le t < \frac{T_i}{2}) = \frac{4VT}{3T_i}$$

$$Q_{ect}(\frac{T_i}{2} \le t \le T_i) = -\frac{8VT}{3T_i^2}.\left(t-\frac{T_i}{2}\right) + \frac{4VT}{3T_i}$$

Decaying Exponential ($\tau=T_i/n$)

$$Q_{ect}(t) = f[VT, T_i]\, e^{\frac{-nt}{T_i}}$$

Decaying Exponential ($\tau=T_i/5$)

$$Q_{ect}(t) = \frac{VT}{0.198652T_i}\, e^{-\frac{5t}{T_i}}$$

Rising Exponential ($\tau=T_i/n$)

$$Q_{ect}(t) = f[VT, T_i]\, e^{\frac{nt}{T_i}}$$

Rising Exponential ($\tau=T_i/5$)

$$Q_{ett}(t) = \frac{0.033918\ VT}{T_i}\ e^{\frac{5t}{T_i}}$$

Ideal Increasing Exponential

$$Q_{ett}(t) = Ae^{\alpha t}$$

t^2

$$Q_{ett}(t) = \frac{3VT.\ t^2}{T_i^3}$$

t^3

$$Q_{ett}(t) = \frac{4VT.\ t^3}{T_i^4}$$

t^n

$$Q_{ett}(t) = \frac{(n+1)\ VT}{T_i^{n+1}} \cdot t^n$$

Where:

$$A = \frac{\alpha}{e^{\alpha T_i}-1}\ VT$$

$$\alpha = \frac{|C_l-C_r|}{C_rC_l|(R_l-R_r)|}$$

$Q_{ett}(t)$ = total flowrate at trachea or endotracheal tube, over time

VT = tidal volume

T_i = inspiratory time

τ = time constant of flowrate change

	n	=	any number
	f [VT, T_i]	=	a constant which is a function of VT and T_i
	t	=	time
25	C_r	=	right lung compliance
	C_l	=	left lung compliance
	R_r	=	right lung resistance
	R_l	=	left lung resistance

39. The method of claim 31 in which said step of selecting an inspiratory waveform comprises selecting at least one of the pressure waveforms, defined as follows:

Constant Pressure

$$P_c(t) = P_c$$

Increasing Pressure

$$P_c(t) = mt$$

Rising Exponential Pressure

$$P_c(t) = P_o e^{\frac{nt}{T_i}}$$

t^2

$$P_c(t) = P_o \left(\frac{t}{T_i}\right)^2$$

t^3

$$P_c(t) = P_o \left(\frac{t}{T_i}\right)^3$$

t^n

$$P_c(t) = P_o \left(\frac{t}{T_i}\right)^n$$

Where: P_c = pressure at carina

m = ramp slope

t = time

T_i = inspiratory time

VT = tidal volume

P_o = an arbitrarily set starting point for the pressure waveform which is iteratively adjusted as the pressure waveform is maintained, and as the actually delivered tidal volume is measured, until the desired tidal volume is obtained

n = any number greater than 1

40. The method of claim 31 in which said step of selecting an inspiratory waveform having an appropriate shape, inspiratory time and inspiratory pause for the lung class of such patient comprises selecting an inspiratory time which is based at least in part on the effective time constant of the entire respiratory system.

41. The method of claim 40 in which said step of selecting an inspiratory time which is based at least in part on the effective time constant of the entire respiratory system comprises:

applying a constant pressure waveform at the carina of the patient through an endotracheal tube with which the patient is intubated;

determining the point at which the flowrate at the endotracheal tube, Q_{ett} (t), is equal to exp (-1) • Q_{max} (0.368 Q_{max}), where Q_{max} is the maximum inspiratory flowrate, which point is the effective time constant of the entire respiratory system.

42. The method of claim 40 in which said step of selecting an inspiratory time which is based at least in part on the effective time constant of the entire respiratory system comprises:

applying an increasing ramp pressure waveform at the carina of a patient through an endotracheal tube with which the patient is intubated;

determining the point at which the flowrate at the endotracheal tube, Q_{et} (t), is equal to (1 - exp (-1) Q_{max} = (1 - 0.368) Q_{max} = 0.632 Q_{max}, where Q_{max} is equal to Q_{et} (T_i) and T_i is the inspiratory time, which point is the effective time constant of the entire respiratory system.

43. The method of determining the class of the lungs of a patient, comprising:

ventilating the patient with an inspiratory waveform having a first inspiratory time;

thereafter ventilating the patient with said inspiratory waveform for a second inspiratory time which is greater than said first inspiratory time throughout a selected time period or number of breaths while maintaining tidal volume constant;

sensing the end-tidal carbon dioxide concentration of the gas exhaled by the patient following each of said inspiratory waveforms, and comparing said sensed concentration of end-tidal carbon dioxide.

44. The method of claim 43 in which said step of thereafter ventilating the patient includes thereafter ventilating the patient with said inspiratory waveform for a second inspiratory time which is greater than said first inspiratory time for at least ten breaths or about one minute while maintaining tidal volume constant.

45. The method of determining the class of the lungs of a patient, comprising:

ventilating the patient with an inspiratory waveform without inspiratory pause;

thereafter ventilating the patient with said inspiratory waveform containing an inspiratory pause while maintaining tidal volume constant for a selected period;

sensing the end-tidal carbon dioxide concentration of the gas exhaled by the patient following each of said inspiratory waveforms, and comparing said sensed concentration of end-tidal carbon dioxide.

46. The method of claim 45 in which said steps of ventilating the patient comprises ventilating the patient with a rising exponential flowrate inspiratory waveform.

47. The method of determining the class of the lungs of a patient, comprising:

ventilating the patient with a constant pressure inspiratory waveform having a selected tidal volume and inspiratory time;

thereafter ventilating the patient with a rising exponential flowrate inspiratory waveform having the same tidal volume and inspiratory time as said constant pressure waveform for a selected period;

sensing the end-tidal carbon dioxide concentration of the gas exhaled by the patient following each of said inspiratory waveforms, and comparing said sensed concentrations of end-tidal carbon dioxide.

48. The method of determining the class of the lungs of a patient, comprising:

ventilating the patient with an inspiratory waveform including an inspiratory pause, said inspiratory waveform being delivered through an endotracheal tube with which the patient is intubated;

measuring the pressure at the carina.

49. The method of claim 48 in which said step of measuring the pressure at the carina comprises sensing the pressure through a sampling port at the distal tip of the endotracheal tube.

50. The method of determining the class of the lungs of a patient, comprising:

ventilating the patient with a constant flowrate waveform;

measuring the pressure at the distal tip of an endotracheal tube with which the patient is intubated during active inflation of the lungs;

examining the resulting intratracheal or carinal pressure trace obtained from such pressure measurements.

51. The method of claim 50 in which said step of examining the resulting intratracheal pressure trace comprises observing whether said pressure trace is linear or non-linear during inspiration.

52. The method of determining the class of the lungs of a patient, comprising:

ventilating the patient with an inspiratory waveform including an inspiratory pause, said inspiratory waveform being delivered through an endotracheal tube with which the patient is intubated;

measuring the pressure at the distal tip of an endotracheal tube with which the patient is intubated during the inspiratory pause;

examining the slope of the resulting intratracheal pressure trace obtained from such pressure measurements.

53. The method of determining the class of the lungs of a patient, comprising:

ventilating the patient with an inspiratory waveform;

measuring the pressure at the distal tip of an endotracheal tube with which the patient is intubated during expiration;

examining the time constants of the resulting intratracheal pressure trace obtained from such pressure measurements.

54. The method of claim 53 in which said step of examining the time constants of the resulting intratracheal pressure trace comprises comparing the time constant of a portion of the pressure trace corresponding to the beginning of exhalation with the time constant of another portion of the pressure trace which corresponds to the end of exhalation.

55. The method of determining the class of the lungs of a patient, comprising:

sensing the intratracheal pressure trace at a beginning segment of exhalation;

sensing the intratracheal pressure trace at an ending segment of exhalation;

taking the natural logarithm of each of said intratracheal pressure traces over time, and comparing the resulting slopes to one another.

56. The method of determining the class of the lungs of a patient, comprising:

ventilating the patient with an inspiratory waveform;

examining the intratracheal pressure trace produced by the inspiratory waveform during active inflation of the lungs, during an inspiratory pause, and, during expiration.

57. The method of claim 56 in which said step of examining the intratracheal pressure trace comprises measuring the pressure at the distal tip of an endotracheal tube with which the patient is intubated.

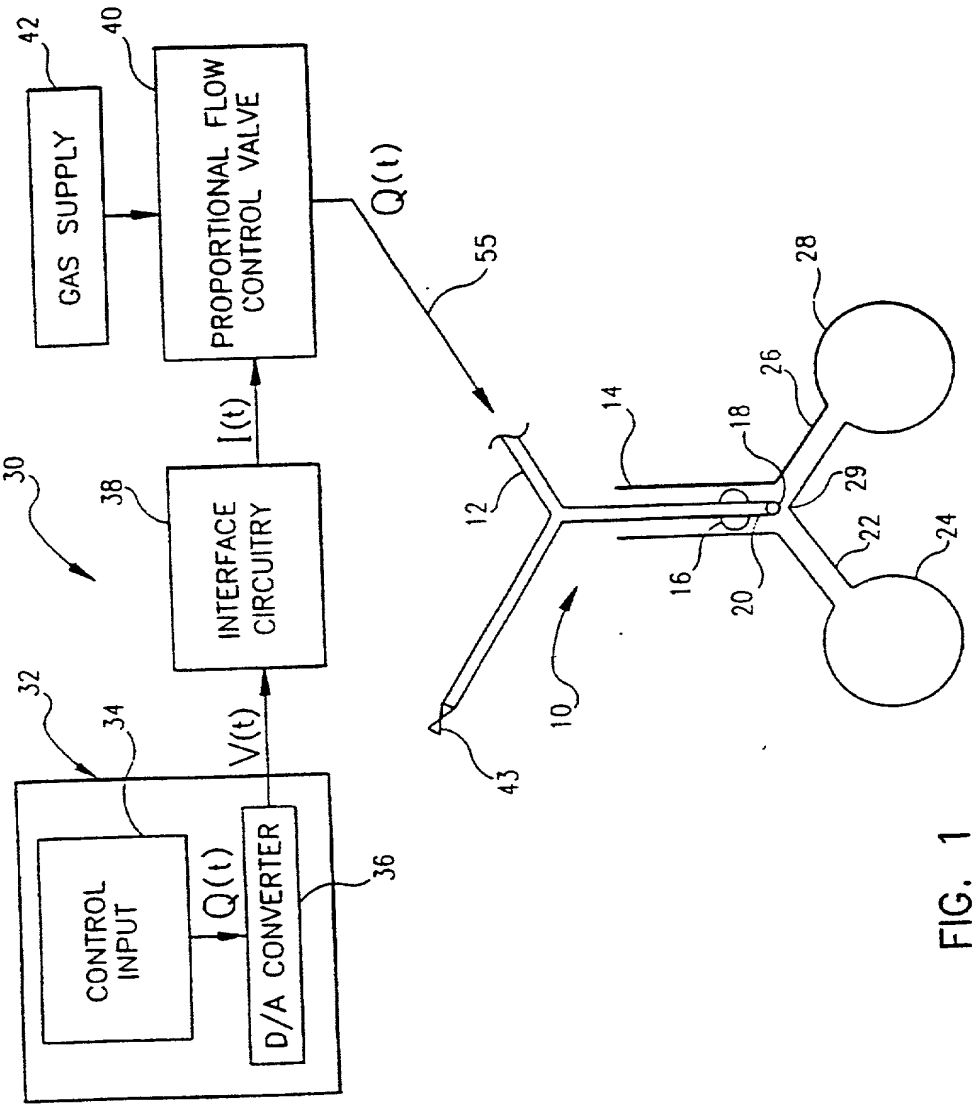
GAS SUPPLY
PROPORTIONAL FLOW CONTROL VALVE
INTERFACE CIRCUITRY
CONTROL INPUT
D/A CONVERTER
Q(t)
I(t)
V(t)
Q(t)
42
40
30
38
32
34
36
55
28
26
14
18
29
12
22
24
16
20
10
43

FIG. 1

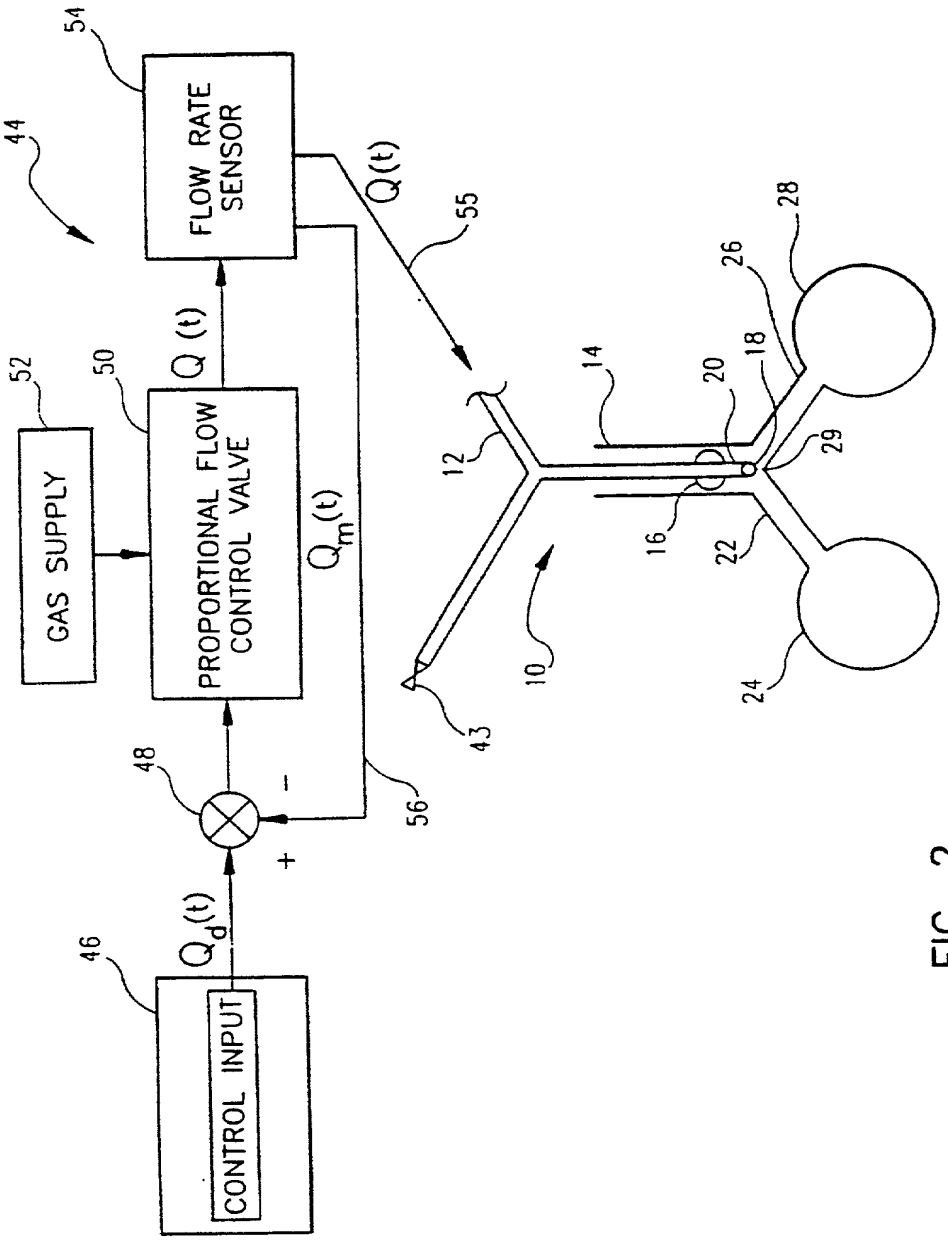
54
FLOW RATE SENSOR
44
Q(t)
55
Q (t)
52
50
GAS SUPPLY
PROPORTIONAL FLOW CONTROL VALVE
$Q_m(t)$
48
56
+
−
$Q_d(t)$
46
CONTROL INPUT
12
14
20
18
26
28
29
16
22
24
10
43

FIG. 2

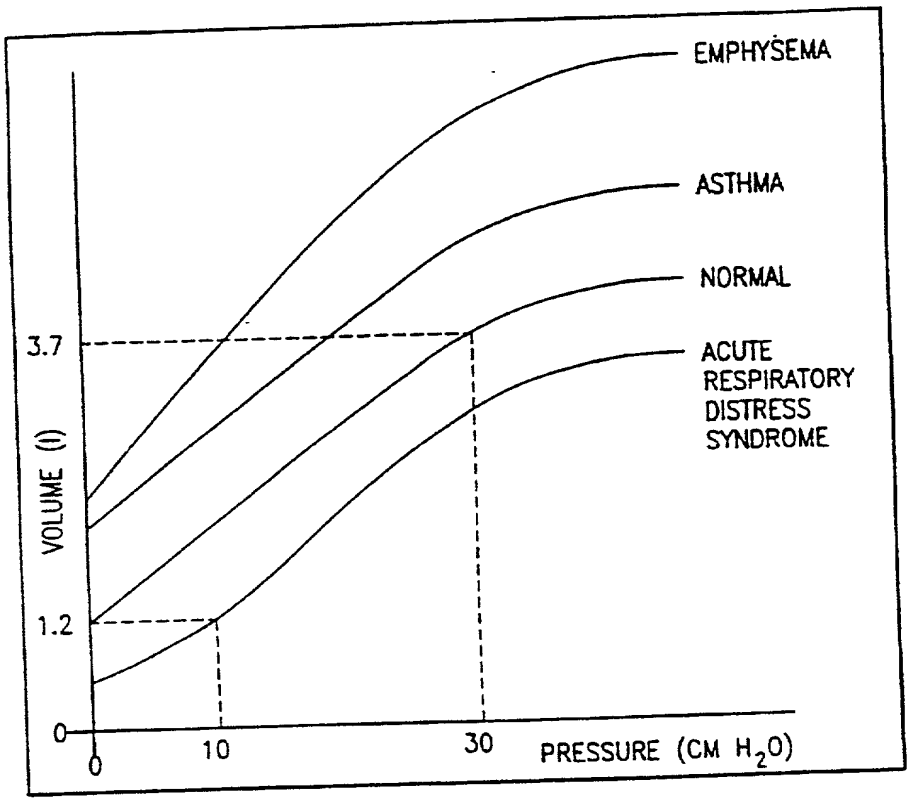
EMPHYSEMA
ASTHMA
NORMAL
ACUTE RESPIRATORY DISTRESS SYNDROME
VOLUME (l)
3.7
1.2
0
0
10
30
PRESSURE (CM H_2O)

FIG. 3

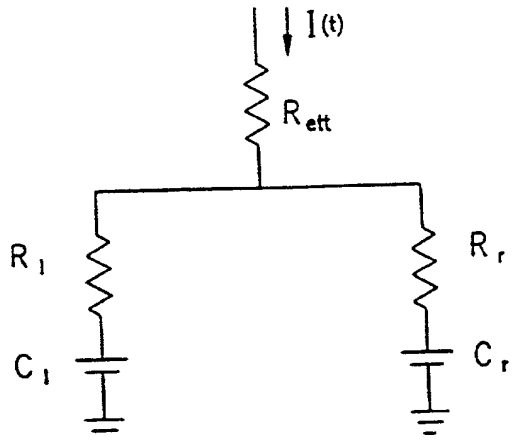
I(t)
R_{ett}
R_l
C_l
R_r
C_r

FIG. 4

	Ventilation Parameters				Before Pause		End of Inspiration					
mode	shape	T_i (s)	VT (l)	pause (% T_i)	V_r/V_t	MLP (cm H_2O)	$R_r(T_i)$ V_r/V_t	MLP (cm H_2O)	PIP (cm H_2O)	Q_{max} (l/min)	system τ (s)	Iter.
flow	const	2.0	0.7	0	-	-	1.000	7.00	15.04	*21.0*	-	-
flow	const	*4.0*	0.7	0	-	-	1.000	7.00	14.52	10.5	-	-
flow	const	2.0	*1.0*	0	-	-	1.000	10.01	21.49	30.0	-	-
flow	const	2.0	0.7	*25*	1.000	7.00	1.000	8.75	15.39	28.0	-	-
flow	inc	2.0	0.7	0	-	-	1.000	4.67	16.09	42.0	-	-
flow	dec	2.0	0.7	0	-	-	1.000	9.34	14.08	42.0	-	-
flow	h-sin	2.0	0.7	0	-	-	1.000	7.00	14.19	33.0	-	-
flow	q-sin	2.0	0.7	0	-	-	1.000	8.92	14.10	33.0	-	-
flow	trap.	2.0	0.7	0	-	-	1.000	8.56	14.10	28.0	-	-
flow	d_exp	2.0	0.7	0	-	-	1.000	11.31	14.05	105.7	-	-
flow	sh-sin	2.0	0.7	0	-	-	1.000	10.36	14.04	57.8	-	-
flow	r_exp	2.0	0.7	0	-	-	1.000	*2.71*	*19.22*	105.4	-	-
press	const	2.0	0.7	0	-	-	1.000	*12.96*	*14.00*	*280.0*	0.15	4
press	inc	2.0	0.7	0	-	-	1.000	6.52	15.13	22.7	-	4
press	r_exp	2.0	0.7	0	-	-	1.000	2.78	19.20	104.8	-	4
flow	inc	2.0	0.7	25	1.000	4.67	1.000	7.00	16.78	56.0	-	-
flow	dec	2.0	0.7	25	1.000	9.34	1.000	10.50	14.14	56.0	-	-
flow	h-sin	2.0	0.7	25	1.000	7.00	1.000	8.75	14.34	44.0	-	-
flow	q-sin	2.0	0.7	25	1.000	8.92	1.000	10.19	14.18	44.0	-	-
flow	trap	2.0	0.7	25	1.000	8.56	1.000	9.92	14.17	37.3	-	-
flow	d_exp	2.0	0.7	25	1.000	11.32	1.000	12.00	14.07	141.0	-	-
flow	sh-sin	2.0	0.7	25	1.000	10.36	1.000	11.28	14.08	77.1	-	-
flow	r_exp	2.0	0.7	25	1.000	2.71	1.000	5.52	20.95	140.5	-	-
press	const	2.0	0.7	25	1.000	12.61	1.000	12.96	14.00	280.0	0.15	4
press	inc	2.0	0.7	25	1.000	6.38	1.000	8.29	15.54	31.1	-	3
press	r_exp	2.0	0.7	25	1.000	2.78	1.000	5.58	20.94	139.8	-	4

Fig. 5

	Ventilation Parameters				Before Pause		End of Inspiration					
mode	shape	T_i (s)	VT (l)	pause (% T_i)	V_p/V_t	MLP (cm H_2O)	$R_{aw}(T_i)$ V_p/V_t	MLP (cm H_2O)	PIP (cm H_2O)	Q_{max} (l/min)	system τ (s)	iter
flow	const	2.0	0.7	0	-	-	0.519	9.45	19.82	*21.0*	-	-
flow	const	*4.0*	0.7	0	-	-	0.509	9.39	19.25	10 5	-	-
flow	const	2.0	*1.0*	0	-	-	0.519	13.50	28.32	30.0	-	-
flow	const	2.0	0.7	*25*	0.525	9.49	0.500	11.79	20.21	28.0	-	-
flow	inc.	2.0	0.7	0	-	-	0.537	6.33	20.97	42.0	-	-
flow	dec	2.0	0 7	0	-	-	0.502	12.57	18.75	42.0	-	-
flow	h-sin	2.0	0.7	0	-	-	0.505	9.45	18.87	33.0	-	-
flow	q-sin	2.0	0.7	0	-	-	0.502	12.01	18.78	33.0	-	-
flow	trap.	2.0	0.7	0	-	-	0.502	11.53	18.77	28.0	-	-
flow	d_exp	2.0	0.7	0	-	-	0.501	15.20	18.73	105.7	-	-
flow	sh-sin	2.0	0.7	0	-	-	*0.500*	13.93	18.71	57.8	-	-
flow	r_exp	2.0	0.7	0	-	-	*0.580*	*3.70*	*24.34*	105 4	-	-
press	const	2.0	0.7	0	-	-	*0.500*	*17.63*	*18.67*	*373.3*	0.106	4
press	inc	2.0	0.7	0	-	-	0.520	8.91	19.89	22.4	-	3
press	r_exp	2.0	0 7	0	-	-	0.579	*3.80*	*24.32*	104.8	-	4
flow	inc	2.0	0 7	25	0.548	6.37	0.500	9.46	21.73	56.0	-	-
flow	dec	2.0	0.7	25	0.503	12.61	0.500	14.12	18.82	56.0	-	-
flow	h-sin	2.0	0 7	25	0.508	9.47	0.500	11.78	19.02	44 0	-	-
flow	q-sin	2.0	0.7	25	0.504	12.05	0.500	13.71	18.86	44.0	-	-
flow	trap	2.0	0 7	25	0.504	11.56	0.500	13.34	18.85	37.3	-	-
flow	d_exp	2.0	0.7	25	0.501	15.25	0.500	16.11	18.75	141.0	-	-
flow	sh-sin	2.0	0 7	25	0.501	13.97	0.500	15.15	18.75	77.1	-	-
flow	r_exp	2.0	0.7	25	0.601	3.72	0.501	7.48	26.18	140.5	-	-
press	const	2.0	0 7	25	0.500	17.27	0.500	17.61	18.65	373	0.106	3
press	inc	2.0	0.7	25	0.528	8 79	0.500	11.27	20.35	30.5	-	3
press	r_exp	2.0	0 7	25	0.600	3.82	0.501	7.56	26.17	139.8	-	4

Fig. 6

	Ventilation Parameters				Before Pause		End of Inspiration					
mode	shape	T_i (s)	VT (l)	pause (% T_i)	V/V_i	MLP (cm H_2O)	$R_{aw}(T_i)$ V/V_i	MLP (cm H_2O)	PIP (cm H_2O)	Q_{max} (l/min)	system τ (s)	iter.
flow	const	2.0	0.7	0	-	-	1.078	7.00	15.57	*21.0*	-	-
flow	const	*4.0*	0.7	0	-	-	1.038	7.00	14.78	10.5	-	-
flow	const	2.0	*1.0*	0	-	-	1.078	10.01	22.24	30.0	-	-
flow	const	2.0	0.7	*25*	1.105	7.01	1.011	8.75	16.09	28.0	-	-
flow	inc.	2.0	0.7	0	-	-	1.143	4.67	17.10	42.0	-	-
flow	dec	2.0	0.7	0	-	-	1.017	9.34	14.22	42.0	-	-
flow	h-sin	2.0	0.7	0	-	-	1.038	7.00	14.49	33.0	-	-
flow	q-sin	2.0	0.7	0	-	-	1.020	8.92	14.27	33.0	-	-
flow	trap.	2.0	0.7	0	-	-	1.022	8.56	14.28	28.0	-	-
flow	d_exp	2.0	0.7	0	-	-	1.006	11.31	14.08	105.7	-	-
flow	sh-sin	2.0	0.7	0	-	-	1.006	10.36	14.14	57.8	-	-
flow	r_exp	2.0	0.7	0	-	-	*1.275*	*2.71*	*21.54*	105.5	-	-
press	const	2.0	0.7	0	-	-	*1.001*	*12.43*	*14.00*	*210.0*	0.188	4
press	inc	2.0	0.7	0	-	-	1.088	6.34	15.76	23.6	-	4
press	r_exp	2.0	0.7	0	-	-	*1.273*	*2.77*	*21.51*	104.9	-	4
flow	inc	2.0	0.7	25	1.186	4.67	1.019	7.00	18.11	56.0	-	-
flow	dec	2.0	0.7	25	1.030	9.34	1.003	10.50	14.38	56.0	-	-
flow	h-sin	2.0	0.7	25	1.063	7.00	1.007	8.75	14.84	44.0	-	-
flow	q-sin	2.0	0.7	25	1.035	8.92	1.004	10.19	14.46	44.0	-	-
flow	trap	2.0	0.7	25	1.039	8.56	1.004	9.92	14.49	37.3	-	-
flow	exp	2.0	0.7	25	1.011	11.32	1.001	12.0	14.11	141.0	-	-
flow	sh-sin	2.0	0.7	25	1.014	10.36	1.002	11.28	14.31	77.1	-	-
flow	r_exp	2.0	0.7	25	1.336	2.71	1.032	5.52	23.96	140.5	-	-
press	const	2.0	0.7	25	1.007	11.96	1.001	12.47	14.05	210.7	0.188	4
press	inc.	2.0	0.7	25	1.123	6.18	1.013	8.13	16.44	32.8	-	3
press	r_exp	2.0	0.7	25	1.334	2.77	1.031	5.58	23.93	139.7	-	3

Fig. 7

	Ventilation Parameters				Before Pause		End of Inspiration					
mode	shape	T_i (s)	VT (l)	pause (% T_i)	V/V_i	MLP (cm H_2O)	$R_{rs}(T_i)$ V/V_i	MLP (cm H_2O)	PIP (cm H_2O)	Q_{max} (l/min)	system τ (s)	iter.
flow	const	2.0	0.7	0	-	-	0.558	9.66	20.76	*21.0*	-	-
flow	const	*4.0*	0.7	0	-	-	0.529	9.50	19.71	10.5	-	-
flow	const	2.0	*1.0*	0	-	-	0.558	13.80	29.65	30.0	-	-
flow	const	2.0	0.7	*25*	0.579	9.76	0.503	12.02	21.45	28.0	-	-
flow	inc	2.0	0.7	0	-	-	0.612	6.53	22.74	42.0	-	-
flow	dec	2.0	0.7	0	-	-	0.508	12.80	19.01	42.0	-	-
flow	h-sin	2.0	0.7	0	-	-	0.520	9.67	19.44	33.0	-	-
flow	q-sin	2.0	0.7	0	-	-	0.510	12.24	19.09	33.0	-	-
flow	trap	2.0	0.7	0	-	-	0.511	11.75	19.11	28.0	-	-
flow	d_exp	2.0	0.7	0	-	-	0.503	15.43	18.78	105.7	-	-
flow	sh-sin	2.0	0.7	0	-	-	0.502	14.16	18.90	57.8	-	-
flow	r_exp	2.0	0.7	0	-	-	*0.739*	*3.86*	*28.18*	105.5	-	-
press	const	2.0	0.7	0	-	-	*0.501*	*16.94*	*18.68*	*280.2*	0.116	4
press	inc	2.0	0.7	0	-	-	0.566	8.80	21.01	23.6	-	3
press	r_exp	2.0	0.7	0	-	-	*0.737*	*3.96*	*28.22*	104.9	-	4
flow	inc	2.0	0.7	25	0.648	6.61	0.505	9.69	24.05	56.0	-	-
flow	dec	2.0	0.7	25	0.515	12.91	0.501	14.35	19.27	56.0	-	-
flow	h-sin	2.0	0.7	25	0.534	9.78	0.501	12.02	19.98	44.0	-	-
flow	q-sin	2.0	0.7	25	0.518	12.35	0.501	13.94	19.40	44.0	-	-
flow	trap	2.0	0.7	25	0.520	11.86	0.501	13.57	19.45	37.3	-	-
flow	d_exp	2.0	0.7	25	0.505	15.56	0.500	16.34	18.82	141.0	-	-
flow	sh-sin	2.0	0.7	25	0.505	14.28	0.500	14.28	19.19	77.1	-	-
flow	r_exp	2.0	0.7	25	0.803	3.92	0.509	7.71	31.06	140.5	-	-
press	const	2.0	0.7	25	0.503	16.43	0.500	16.99	18.75	281.3	0.116	4
press.	inc.	2.0	0.7	25	0.593	8.70	0.503	11.23	21.92	32.7	-	3
press	r_exp	2.0	0.7	25	0.800	4.01	0.509	7.79	31.03	139.8	-	3

Fig. 8

	Ventilation Parameters				Before Pause		End of Inspiration					
mode	shape	T_i (s)	VT (l)	pause (% T_i)	V_r/V_i	MLP (cm H_2O)	$R_s(T_i)$ V_r/V_i	MLP (cm H_2O)	PIP (cm H_2O)	Q_{max} (l/min)	system τ (s)	iter
flow	const	2.0	0.7	0	-	-	2.891	7.12	15.44	*21.0*	-	-
flow	const	*4.0*	0.7	0	-	-	2.945	7.07	14.72	10.5	-	-
flow	const	2.0	*1.0*	0	-	-	2.891	10.18	22.05	30.0	-	-
flow	const	2.0	0.7	*25*	2.855	7.16	2.992	8.88	15.92	28.0	-	-
flow	inc.	2.0	0.7	0	-	-	2.804	4.78	16.87	42.0	-	-
flow	dec	2.0	0.7	0	-	-	2.981	9.47	14.16	42.0	-	-
flow	h-sin	2.0	0.7	0	-	-	2.957	7.13	14.37	33.0	-	-
flow	q-sin	2.0	0.7	0	-	-	2.977	9.05	14.20	33.0	-	-
flow	trap	2.0	0.7	0	-	-	2.975	8.69	14.20	28.0	-	-
flow	d_exp	2.0	0.7	0	-	-	2.993	11.44	14.07	105.7	-	-
flow	sh-sin	2.0	0.7	0	-	-	2.995	10.49	14.09	57.8	-	-
flow	r_exp	2.0	0.7	0	-	-	*2.637*	*2.80*	*21.13*	105.5	-	-
press	const	2.0	0.7	0	-	-	*3.000*	*12.69*	*14.00*	*209.9*	0.197	4
press	inc	2.0	0.7	0	-	-	2.878	6.49	15.60	23.4	-	4
press	r_exp	2.0	0.7	0	-	-	*2.640*	*2.8*	*21.10*	104.8	-	4
flow	inc	2.0	0.7	25	2.750	4.81	2.986	7.13	17.82	56.0	-	-
flow	dec	2.0	0.7	25	2.967	9.51	2.998	10.64	14.28	56.0	-	-
flow	h-sin	2.0	0.7	25	2.927	7.17	2.996	8.88	14.65	44.0	-	-
flow	q-sin	2.0	0.7	25	2.960	9.09	2.998	10.32	14.34	44.0	-	-
flow	trap	2.0	0.7	25	2.956	8.73	2.998	10.05	14.36	37.3	-	-
flow	d_exp	2.0	0.7	25	2.989	11.49	3.000	12.13	14.09	141.0	-	-
flow	sh-sin	2.0	0.7	25	2.988	10.54	3.000	11.41	14.19	77.1	-	-
flow	r_exp	2.0	0.7	25	2.568	2.82	2.975	5.65	23.48	140.5	-	-
press	const	2.0	0.7	25	2.996	12.27	3.000	12.70	14.01	210.2	0.197	4
press	inc	2.0	0.7	25	2.834	6.35	2.991	8.28	16.21	32.4	-	3
press	r_exp	2.0	0.7	25	2.571	2.88	2.976	5.71	23.45	139.7	-	3

Fig. 9

	Ventilation Parameters				Before Pause		End of Inspiration					
mode	shape	T_i (s)	VT (l)	pause (% T_i)	V_r/V_i	MLP (cm H_2O)	$R_s(T_i)$ V_r/V_i	MLP (cm H_2O)	PIP (cm H_2O)	Q_{max} (l/min)	system τ (s)	iter.
flow	const	2.0	0.7	0	-	-	2.000	9.34	20.06	*21.0*	-	-
flow	const	*4.0*	0.7	0	-	-	2.000	9.34	19.36	10.5	-	-
flow	const	2.0	*1.0*	0	-	-	2.000	13.34	28.65	30.0	-	-
flow	const	2.0	0.7	25	2.000	9.34	2.000	11.67	20.52	28.0	-	-
flow	inc.	2.0	0.7	0	-	-	2.000	6.23	21.45	42.0	-	-
flow	dec	2.0	0.7	0	-	-	2.000	12.44	18.77	42.0	-	-
flow	h-sin	2.0	0.7	0	-	-	2.000	9.33	18.92	33.0	-	-
flow	q-sin	2.0	0.7	0	-	-	2.000	11.89	18.80	33.0	-	-
flow	trap.	2.0	0.7	0	-	-	2.000	11.41	18.79	28.0	-	-
flow	d_exp	2.0	0.7	0	-	-	2.000	15.08	18.74	105.7	-	-
flow	sh-sin	2.0	0.7	0	-	-	2.000	13.81	18.71	57.8	-	-
flow	r_exp	2.0	0.7	0	-	-	2.000	*3.61*	*25.63*	105.5	-	-
press	const	2.0	0.7	0	-	-	2.000	*17.28*	*18.67*	*280.0*	0.15	4
press	inc	2.0	0.7	0	-	-	2.000	8.70	20.17	22.7	-	4
press	r_exp	2.0	0.7	0	-	-	2.000	*3.70*	*25.59*	104.8	-	4
flow	inc	2.0	0.7	25	2.000	6.23	2.000	9.34	22.37	56.0	-	-
flow	dec	2.0	0.7	25	2.000	12.45	2.000	14.00	18.85	56.0	-	-
flow	h-sin	2.0	0.7	25	2.000	9.33	2.000	11.67	19.11	44.0	-	-
flow	q-sin	2.0	0.7	25	2.000	11.89	2.000	13.59	18.90	44.0	-	-
flow	trap	2.0	0.7	25	2.000	11.41	2.000	13.22	18.90	37.3	-	-
flow	d_exp	2.0	0.7	25	2.000	15.09	2.000	15.99	18.76	141.0	-	-
flow	sh-sin	2.0	0.7	25	2.000	13.82	2.000	15.04	18.77	77.1	-	-
flow	r_exp	2.0	0.7	25	2.000	3.61	2.000	7.36	27.94	140.5	-	-
press	const	2.0	0.7	25	2.000	16.81	2.000	17.28	18.67	280.0	0.15	4
press	inc.	2.0	0.7	25	2.000	8.51	2.000	11.05	20.72	31.1	-	3
press.	r_exp	2.0	0.7	25	2.000	3.70	2.000	7.44	27.92	139.8	-	4

Fig. 10

	Type 1 $R_1 = R_2$ $C_1 = C_2$ $\tau_1 = \tau_2$	Type 2 $R_1 = R_2$ $C_1 \neq C_2$ $\tau_1 \neq \tau_2$	Type 3 $R_1 \neq R_2$ $C_1 = C_2$ $\tau_1 \neq \tau_2$	Type 4 $R_1 < R_2$ $C_1 < C_2$ $\tau_1 \neq \tau_2$	Type 5 $R_1 < R_2$ $C_1 > C_2$ $\tau_1 \neq \tau_2$	Type 5a $R_1 < R_2$ $C_1 > C_2$ $\tau_1 = \tau_2$
Influence of shape on R_L	none	yes	yes	yes	yes	none
Shape *without pause* with R_L closest to 1.0	all shapes: $R_L = 1.0$	inc. exp. flow/press.	const press.	inc. exp. flow/press	inc. exp flow/press	all shapes $R_L = C_2/C_1$
Shape *without pause* with R_L farthest from 1.0	$R_L = 1.0$ for all shapes	const press. sh-sin flow	inc. exp. flow/press.	const press. sh-sin flow	const press. sh-sin flow	$R_L = C_2/C_1$ for all shapes
Shape with lowest mean lung pressure over time	inc. exp flow/press.	inc. exp. flow/press.	inc. exp. flow/press.	inc. exp. flow/press	inc. exp flow/press.	inc. exp flow/press
Shape with highest mean lung pressure over time	const press.	const press.	const press.	const press.	const press	const press.
Effect of increased T_I on $R_L = V_2/V_1$	none for all shapes	worse or no improvement for all shapes	improved for all shapes	worse for all shapes	worse for all shapes	none for all shapes
Effect of increased T_I on MLP(T_I)	none for all flow shapes & r_exp, press.; ↑ for other press. shapes	↓ for all flow shapes and r_exp, press.; ↑ for other press. shapes;	none for all flow shapes & r_exp, press.; ↑ for other press. shapes	↓ for all flow shapes & r_exp, press; ↑ for other press shapes	↓ for all flow shapes & r_exp, press, ↑ for other press. shapes	none for all flow shapes & r_exp, press, ↑ for other press. shapes
Effect of inspiratory pause on R_L	none for all shapes	worse or no improvement for all shapes	better for all shapes; const press. unchanged	worse for all shapes	worse for all shapes, const press unchanged	none for all shapes
Effect of inspiratory pause on MLP(T_I)	↑ for all shapes; none for const press.	↑ for all shapes; none for const press.	↑ for all shapes; none for const press.	↑ for all shapes; none for const press.	↑ for all shapes; none for const press	↑ for all shapes; none for const press.
Effect of increased VT with const flow shape	none on R_L ↑ MLP, ↑ PIP	none on R_L ↑ MLP, ↑ PIP	none on R_L ↑ MLP, ↑ PIP	none on R_L ↑ MLP, ↑ PIP	none on R_L ↑ MLP, ↑ PIP	none on R_L ↑ MLP, ↑ PIP
Lowest pressure at carina (PIP)	const press	const press.	const press.	const press	const press.	const press.
Highest pressure at carina (PIP)	inc. exp. flow/press.	inc. exp. flow/press.	inc. exp. flow/press.	inc. exp. press./flow	inc. exp. flow/press.	inc. exp flow/press.

Fig. 11

2002

Combined Declaration and Power of Attorney

09/936

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

CONTROL OF SUPPLIED PRESSURE IN ASSISTED VENTILATION

the specification of which *(check one)* ☐ is attached hereto. ☑ was filed on May 5, 2000, as United States Application Serial No. 09/936,854 or PCT International Application No. PCT/AU00/00411, and was amended on _____ (if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information that is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, §119 (a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT international application which designated at least one country other than the United States of America, or Title 35, United States Code, §371, listed below and have also identified below, by checking the appropriate box, any foreign application for patent or inventor's certificate, or of any PCT application having a filing date before that of the application on which priority is claimed:

Prior Foreign Application(s)			Priority claimed	
PQ0198	AUSTRALIA	MAY 6, 1999	☐	☐
(Number)	(Country)	Day/month/year filed	Yes	No
_____	_____	_____	☐	☐
(Number)	(Country)	Day/month/year filed	Yes	No

I hereby claim the benefit under Title 35, United States Code, § 119(e) of any United States provisional application(s) listed below:

_____ (Application No.) _____ (Filing Date)

I hereby claim the benefit under Title 35, United States Code, §120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, §112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56 which occurred between the filing date of the prior application and the national

or PCT international filing date of this application:

(Application No.)	(Filing date)	(Status - patented, pending, abandoned)
(Application No.)	(Filing date)	(Status - patented, pending, abandoned)

And I hereby appoint:

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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I am or have reason to believe that I am the executor of the estate of the above deceased inventor. I have reviewed this declaration as if signed by the inventor, and upon information and belief, I hereby state that the above listed facts required to be made by the inventor are believed to be true. I am aware that willful false statements and the like are punishable by fine or imprisonment, or both and may jeopardize the validity of the application or any patent issuing thereon.

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